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The tectono-metamorphic evolution of the Cretaceous northern Adriatic margin as recorded by sedimentary series (western part of the Eastern Alps)

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Key words: Eastern Alps, Cretaceous, Adriatic plate, geodynamics, obduction/subduction, clastic sedimentary basins, melanges, blueschists, heavy minerals

ABSTRACT

Cretaceous convergence between the Penninic oceanic and Adriatic continental plates is recorded by coeval terrigeneous clastic sediments preserved in melange zones and Austroalpine units. This paper firstly reviews the possible provenance of the detrital grains. Their composition and spatial distribution gives evidence for the presence of two main source areas. One was situated along the northern Adriatic margin (interpreted as the North-Adriatic obduction belt), the other along the southern margin of the Austroalpine domain, the Vardar suture zone (Tethyan suture zone of other authors). Both sources included mixed continental and oceanic rock associations. In addition, the North-Adriatic obduction belt supplied blueschist metamorphic mineral grains. The corresponding metamorphic event is tentatively correlated with the Early Cretaceous convergence along the Penninic-Austroalpine margin. The lack of convergence-related calc-alkaline volcanism and ordered accretionary prism formation suggests that south dipping Penninic oceanic subduction under the Adriatic margin did not drive blueschist metamorphism and ophiolite uplift. Instead, early convergence is paralleled by extension and alkaline volcanic activity from sub-continental mantle source within the Adriatic plate. The combination of geodynamic and sedimentary arguments suggests an Oman-type dip-slip regime for the formation of the North-Adriatic obduction belt. In front of this belt, on the Adriatic (Austroalpine) leeway, a foreland basin was generated receiving increasingly oceanic, continental and blueschist metamorphic detritus from this source. This northern source vanished during Late Coniacian to Santonian. From the Santonian-Campanian on the Vardar suture zone became a dominant source of sediment particles.

ZUSAMMENFASSUNG

Die kretazische Konvergenz zwischen der penninischen Ozeanplatte und der adriatischen (austroalpinen) Kontinentalplatte wird in gleichaltrigen, terrigenklastischen Sedimentserien abgebildet. Die Sedimente sind in Melangezonen und als kohärente Serien in den ostalpinen Decken erhalten. Der vorliegende Artikel gibt zuerst eine Übersicht über die vermutliche Herkunft des klastischen Detritus. Die Art und die räumliche Verteilung des Materials bestätigt die Anwesenheit von zwei Hauptquellen. Ein Liefergebiet lag am nördlichen Rand der Adria-Platte, das im folgenden als kretazischer Obduktionsgürtel interpretiert wird (Nord-adriatischer Obduktionsgürtel). Das andere befand sich am südlichen Rand der Adria-Platte und wird mit der Vardar-Suturzone korreliert (Tethys-Suturzone anderer Autoren). Von beiden Liefergebieten wurde gemischter, kontinentaler und ozeanischer Schutt in die Becken geschüttet. Der Nord-adriatische Obduktionsgürtel lieferte auch Detritus von Blauschiefer-Gesteinen. Es wird angenommen, dass diese Blauschiefer-Metamorphose ein alpines kretazisches Ereignis ist. Im Anschluss wird ein geodynamisches Modell für die Bildung des Nord-adriatischen Obduktionsgürtels entwickelt. Die Abwesenheit von kretazischem calc-alkalischem Vulkanismus und das Fehlen von geordneten Akkretionsprismen deutet darauf hin, dass die Blauschiefermetamorphose und die Hebung

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von ozeanischen Serien nicht durch kontinuierliche, südgerichtete Subduktion der penninischen Ozeanplatte unter den adriatischen Kontinent verursacht wurde. Im Gegenteil, die frühe Konvergenz wird von Extension und alkalischem Vulkanismus von einer sub-kontinentalen Mantelquelle in der adriatischen Platte begleitet. Die Kombination der geodynamischen und sedimentologischen Argumente weist darauf hin, dass ein mit dem spätkretazischen Oman-Rand vergleichbares dip-slip-Regime die Obduktion von penninischer Ozeankruste auf den adriatischen Kontinentalrand bewirkt hat. Entlang der Stirn dieses Obduktionsgürtels bildete sich auf der adriatischen Platte ein Vorland-Becken aus, das ab der späten Unterkreide zunehmend mit ozeanischem, kontinentalem und blauschiefer-metamorphem Detritus beliefert wurde. Der Sedimenteintrag von dieser nördlichen Quelle versiegte während des späten Coniacien und Santonien. Ab dem Santonien und Campanien wurde die Vardar Suturzone die dominierende Sedimentquelle im austroalpinen Bereich.

Introduction

After Jurassic to Early Cretaceous extension und ocean formation the Penninic-Adriatic margin turned to convergence during late Early Cretaceous (e.g. Weissert & Bernoulli 1985, Winkler & Bernoulli 1986, Winkler 1988). Convergence-related sediments consist of turbiditic deep-water deposits (also referred to as flysch deposits), shallow marine and continental formations. The detrital composition of the clastic series indicates the convergence-related emergence of variably composed ophiolitic and continental basement source terrains. The age of sediment formation, composition and mode of formation is expected to reflect the tectonic processes which have driven both uplift and erosion of crustal portions and the subsidence leading to basin formation.

Vestiges of the Penninic oceanic domain and of the Lower Austroalpine distal continental margin series are preserved in the Arosa zone, a complex unit of imbricates and melange formations (Fig. 1, 2, e.g. Dietrich & Franz 1976; Bernoulli & Weissert 1985; Lüdin 1987; Winkler 1988). Clastic series deposited on the Adriatic (Austroalpine) continental margin are present as coherent turbiditic deep-water formations in the Allgäu and Lechtal nappes of the Northern Calcareous Alps (NCA) and in imbricates and melanges as in the Randzone of the NCA and the Walsertal zone (see Fig. 1, 2, e. g. Gaupp 1980, Weidich 1984, Winkler 1988). A great wealth of published work provides information on the stratigraphical range, mode of deposition and detrital composition of the Upper Cretaceous Gosau series in the central and eastern NCA (Fig. 3), which is subdivided into a Lower and an Upper Gosau Group (e.g. Faupl et al. 1987; Wagreich & Faupl 1994). The Lower Gosau Group comprises essentially continental and shallow marine sequences, the Upper Gosau Group deep-water turbiditic deposits. The alluvial to deep-water Central Alpine Gosau series in southeastern Austria (Fig. 3) overlies unconformably Upper Austroalpine nappes of the Graz Palaeozoic and Gurktal nappe system (e.g. Gollner et al. 1987; Wagreich & Faupl 1994).

From structural and tectonic work it has been established that the Penninic and Austroalpine domains experienced important reorganisation related to the change from an extensional to a compressive tectonic regime sometime during the Early Cretaceous. Generally, Cretaceous top to the W or NW compressive movements are reported from Austroalpine units (e.g. Ratschbacher 1986; Fritz 1988; Ring et al. 1988; Froitzheim et al. 1994). Consequently, and assuming an approximately E-W orientation of the Penninic-Adriatic boundary (Fig. 4), this should also have induced important E-W parallel transcurrent movements (e.g. Ratschbacher 1986).

Compared with the Jurassic rift-related clastic formations, the Cretaceous convergence-related sedimentary formations reveal significant changes in pebble and clastic

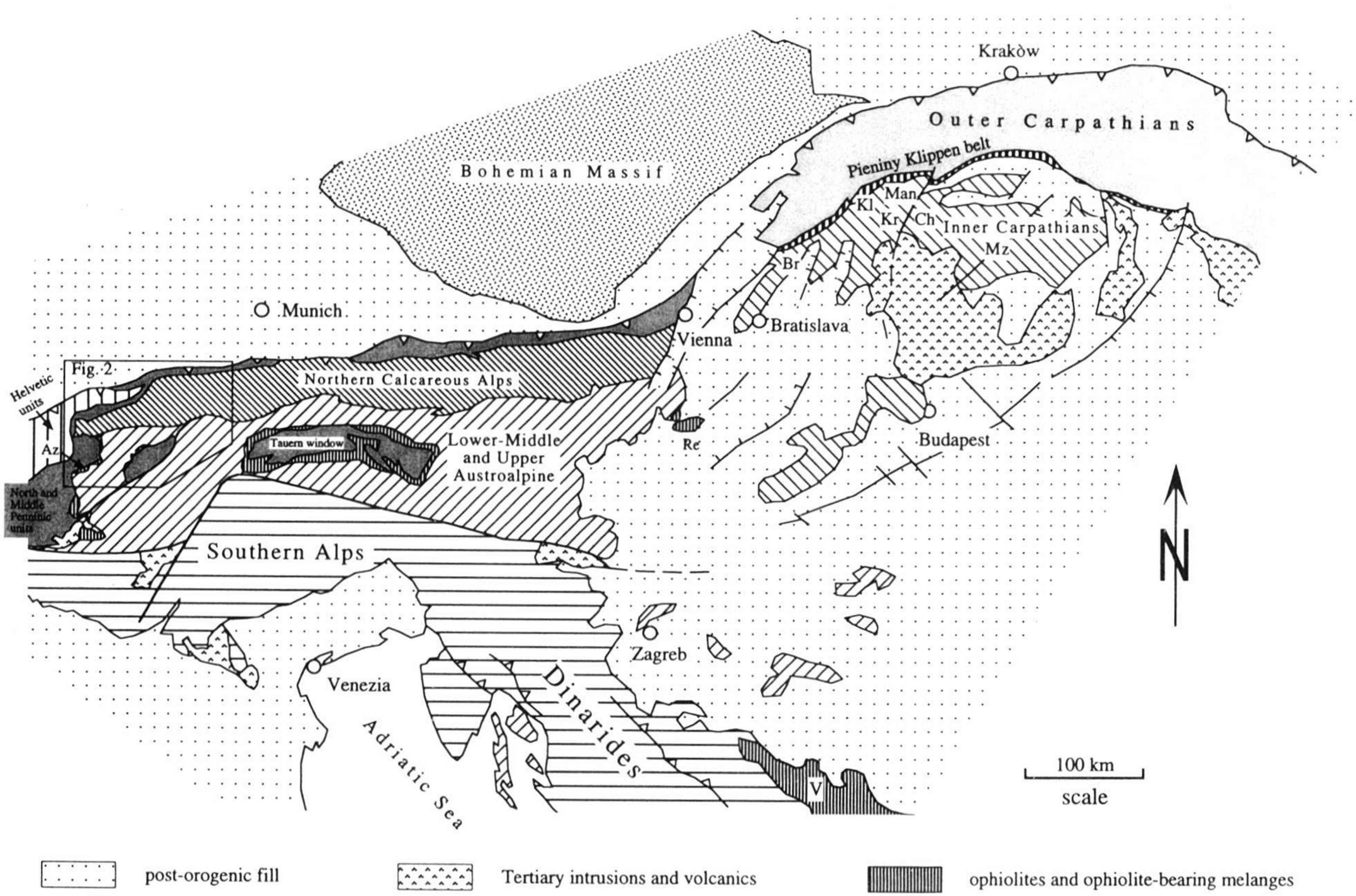

Fig. 1. Schematic geological map of the Eastern Alps and Western Carpathians showing the main tectono-stratigraphic units to which is referred in the text. Key: Az = Arosa zone, Br = Brezovské Karpaty, Ch = Choc unit, Kl = Klape unit, Kr = Krisna unit, Man = Manin unit, Mz = Meliata zone, Re = Rechnitz window, V = Vardar ophiolite zone.

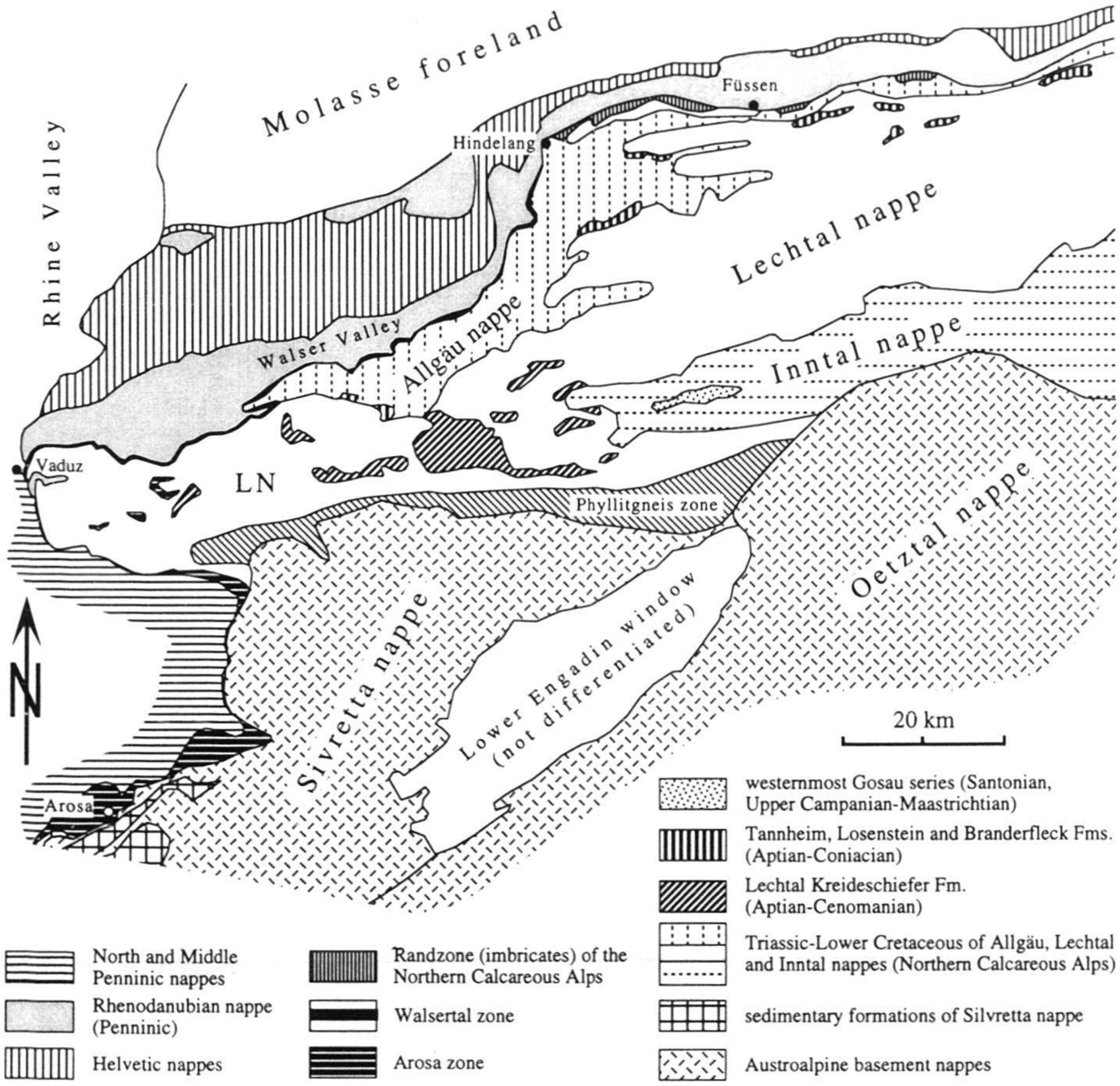

Fig. 2. Simplified geological map of the western part of the Eastern Alps depicting the main tectono-stratigraphic units. Note the transition of the melange-bearing Walsertal zone to the Randzone (imbricate zone) of the NCA at Hindelang. The Randzone consists mainly of Lower Cretaceous limestone formations and the Tannheim-Losenstein-Branderfleck Group. In comparison to the ophiolite-bearing Arosa zone, in the Walsertal zone only a few ophiolitic slivers are present. The palinspastic sections in Fig. 5 cross the presented area in approximatively NW-SE direction.

mineral composition (Lüdin 1987; Winkler 1988). These changes include an increase of the variety of pebble and mineral clasts, and in particular, the appearance of clasts derived from oceanic crust and of suspected convergence-related blueschist metamorphic terrains (Winkler & Bernoulli 1986; Winkler 1988). Obviously, general (oblique) convergence along the Penninic-Adriatic margin created new areas for erosion. Related volcanic activity is scarce and consists of alkaline basanitic dykes (ehrwaldites) cutting across Jurassic and Cretaceous sediments (Radiolarite Fm., Aptychus Limestone Fm., Trommsdorff 1962) in the Lechtal nappe. Total rock potassium/argon and zircon fission track measurements point to an intrusion age of ca. 100 Ma (Trommsdorff et al. 1990; Seward

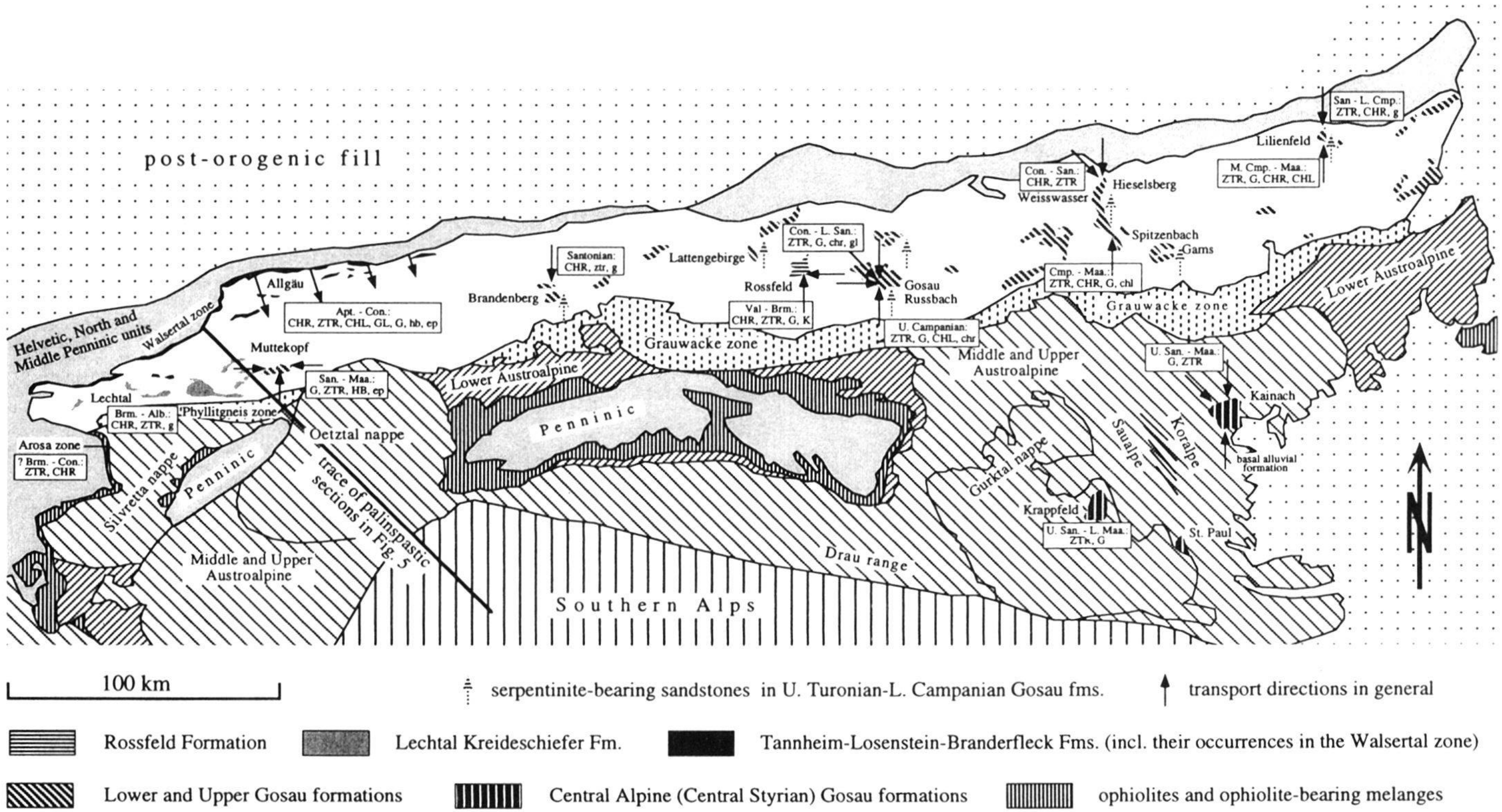

Fig. 3. Map of the Northern Calcareous Alps (white fill) and related tectonic units (compiled after Frank 1987, Winkler 1988 and Wagreich & Faupl 1994). For various Cretaceous sedimentary series in the NCA the site of sediment supply and the major heavy mineral content is indicated qualitatively. Abbreviations: CHL = chloritoid, CHR = chromian spinel, EP = Epidote, G = garnet, GL = blue amphibole, HB = amphibole, K = kaersutite, ZTR = zircon + tourmaline + rutile. Minor mineral grain occurrences are indicated with small letters.

and Trommsdorff pers. comm. 1995). Notably, the deep-seated sub-continental mantle source of these volcanics is not compatible with the presence of a subduction zone crossing at that time, or earlier the pathway of the rising magmas (Trommsdorff et al. 1990). In the Alpine domain, possible subduction induced calc-alkaline magmatism (Adamello intrusion, dykes in the Ortler nappe) and reworking of volcanic arc material only appears during the late orogenic stage in the Eocene. The position of that Taveyannaz arc is a matter of debate (e.g. Waibel 1993), but it is definitively too young to be correlated with the very early Cretaceous history of convergence. Metamorphic ages interpreted in Austroalpine basement and cover series mostly document Late Cretaceous tectonic events. Only few data point to Early Cretaceous tectonic activity (see e.g. Winkler & Bernoulli 1986; Winkler 1988).

Shaping of the problem

We are confronted with the enigmatic situation that the Cretaceous Penninic-Adriatic sediment record implies the generation of new detrital sources. In particular, this applies to the formation of various oceanic basement- and blueschist-bearing ("exotic") terrains. However, the required long lasting subduction for oceanic basement and blueschist metamorphic rock uplift is not indicated by coeval volcanic activity and ordered accretionary prism formation. The application of conventional subduction models with continuous southward dipping subduction of the Penninic ocean under the Adriatic margin fails, because of the lack of calc-alkaline volcanism and the early appearance of blueschist detritus during the Albian in the Adriatic margin series (Winkler 1988). Also by taking into account a delay of several tens of Ma to acquire a sufficiently long Penninic oceanic slab (ca. 400 km) subducted (to initiate a continental arc volcanism) does not help to solve the controversy.

Petrographic and palaeotransport data from the convergence-related Cretaceous sediment series in the Eastern Alps suggest the presence of two main sources of the detrital material. One can be allocated to the hypothetical ridge which formed along the northern Adriatic (Austroalpine) margin (Rumunischer or Ultrapienidischer Rücken of earlier investigators, see e.g. Faupl 1978; Winkler 1988). The other source may be correlated with the presumably earlier closing of the Vardar oceanic domain to the south or southeast of the Austroalpine domain (also so-called Tethyan suture zone, e.g. Pober & Faupl 1988; Wagreich & Faupl 1994). Both source areas may have provided oceanic and blueschist metamorphic mineral grains which are of great interest for geodynamic interpretations. Evidence from the sediment series will allow the development of a more refined picture.

In order to approach the problem of the location of the blueschist metamorphic and ophiolitic source areas I shall review a variety of sedimentological, stratigraphical and petrographical (mainly heavy mineral) data which reliably constrain the derivation of the clastic material. The resulting arguments will be combined to propose an alternative obduction model for the Cretaceous evolution of the northern Adriatic margin. They are thought to be compatible with general geodynamic implications as the missing calc-alkaline volcanic activity and the mode of oceanic basement and blueschist metamorphic series uplift as documented by the sedimentary record.

Because of the close resemblance to the present topic, some comparisons with the Western Carpathians (Fig. 1) will be presented. The Cretaceous clastic series show a sim-

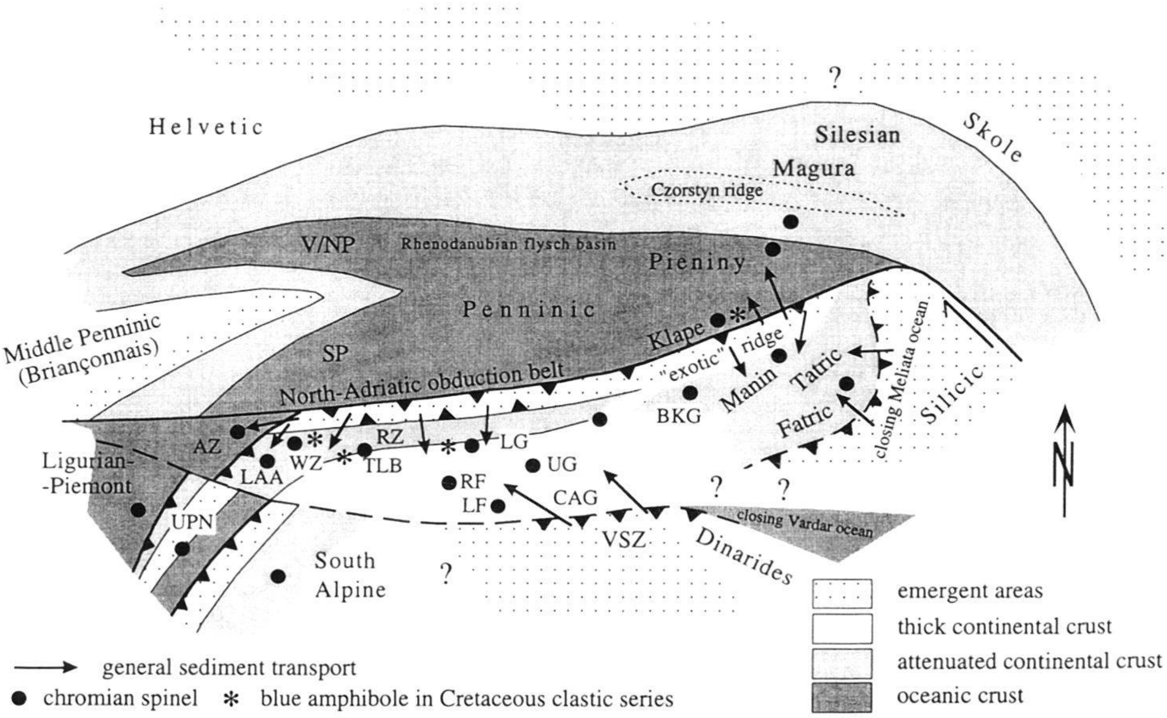

Fig. 4. Palinspastic sketch of the Albian situation in the Eastern Alpine and Carpathian domains summarizing the supply of ophiolitic and blueschist metamorphic grains. Compiled after Dercourt et al. (1990), Rakus et al. (1990), Winkler & Slaczka (1994), Ricou (1994) and Wagreich & Faupl (1994). For the Middle Penninic, an eastern termination is assumed for the area representing approximatively the actual boundary between Western and Eastern Alps (see also Trümpy 1992). East of this meridian a single Penninic domain is suggested. Key: AZ = Arosa zone, BKG = Brezovské Karpaty Gosau, CAG = Central Alpine Gosau, LAA = Lower Austroalpine, LF = Lavant Fm., LG = Lower Gosau Group, RF = Rossfeld Formation, RZ = Randzone of NCA, SP = South Penninic, TLB = Tannheim-Losenstein-Branderfleck Group, UG = Upper Gosau Group, UPN = Upper Prealpine nappe, V/NP = Valais/North Penninic, VSZ = Vardar suture zone, WZ = Walsertal zone.

ilar timing in the occurrence of ophiolitic and blueschist detrital grains as in the Eastern Alps. The formation of an "exotic" ridge during the closing of the older Triassic-Early Jurassic Pieniny-Meliata oceanic domain is interpreted to have triggered the uplift and exhumation of ophiolitic and blueschist metamorphic rocks.

Sources of the detrital grains

Chromian spinel is the characteristic mineral grain in Cretaceous Penninic, Lower and Upper Austroalpine units of the Eastern Alps (Wildi 1985). This observation goes back to Woletz (1963) and has been confirmed by many other authors. As suggested early by Dietrich & Franz (1976), reworked chromian spinel, serpentinite and basalt grains can be reliably assumed to have been derived from uplifted Alpine Mesozoic oceanic basement. Typically, the ophiolitic detritus is associated with variable amounts of clasts derived from Adriatic (Austroalpine) continental margin basement and sedimentary cover series. Generally, it can be assumed that during convergence at the Adriatic margin, composite source terrains were uplifted and reworked into adjacent basins. Chemical investigations on detrital chromian spinels prove their derivation from lherzolitic mantle rocks (Pober & Faupl 1988).

Along the northern Adriatic margin, good evidence for the derivation from mixed Penninic/Adriatic source terrains comes from the Arosa zone and the western NCA (Fig. 1, 2). In the Arosa zone ophiolitic basement detritus is associated with other detrital grains derived from the sedimentary cover, in particular also with siliceous Palombini limestone clasts from the Penninic oceanic series (Lüdin 1987). In the Lower to Upper Cretaceous Tannheim, Losenstein and Branderfleck Formations of the western NCA (Fig. 2) the co-occurrence of ophiolitic detrital grains with Austroalpine Variscan basement and Mesozoic sedimentary cover pebbles is well documented (Gaupp 1983; Winkler 1988). In contrast, chromian spinel grains are generally lacking in older, Jurassic, Lower Austroalpine syn-rift clastic formations (Lüdin 1987; Häusler 1988; Winkler 1988). The scarce occurrence of chromian spinel in pre-Cretaceous sediment series may be partly due to the erosion of Variscan suture zones which were present in the Adriatic basement. On the other hand, local ultrabasic detritus, including chromian spinel, may have been derived from cliffs in the distensive Lower Austroalpine continental margin where ultrabasic rocks were exhumed (Häusler 1988). Alternatively, also the supposedly earlier closing Vardar ocean may have provided chromian spinel grains to older sediment series. However, in the present discussion I refer primarily to the abundant occurrence of chromian spinel in the Cretaceous deposits of the Austroalpine domain.

A similar argument can be applied partly to the detrital blueschist mineral grains (including rare lawsonite) present in the western NCA and the Randzone of the NCA (Miller 1977; Faupl 1984; Winkler & Bernoulli 1986; Winkler 1988) which are documented from the Middle Albian onward (Winkler 1988). These grains are not observed in the rift-related Jurassic series. In addition, the delicate chemistry of the blueschist minerals (glaucophane, Fe-glaucophane, crossite; Miller 1977; Winkler 1988) most probably rules out a derivation from the polymetamorphic Varscan basement. There, the final regional greenschist metamorphic overprint would have altered such a mineral assemblage. Also, no occurrence of rocks with a corresponding mineral grain paragenesis is known from the remaining Variscan basement of the Eastern Alpine margin (Chr. Miller written comm. 1995). For these reasons an Alpine blueschist metamorphic origin as proposed by Winkler & Bernoulli (1986) and Winkler (1988) can be assumed for these mineral grains.

In the western part of the NCA (Fig. 2) considerable amounts of chloritoid, garnet and epidote (partly clinozoisite) mineral grains are observed in pre-Santonian sediments. Their pertinent co-occurrence with blue amphibole and their general close stratigraphical and regional association (Winkler 1988) suggests that they may originate from Alpine greenschist metamorphic series which were genetically associated with the blueschist metamorphic series. The occurrence of a few percent of magnesio-hornblende and ferrotschermakite in northern Lechtal nappe heavy mineral separates (Kaltwasserlaine section, Winkler 1988) indicates the presence of high-grade metamorphic rocks in the source area. In the Upper Gosau formations garnet is a main component in the heavy mineral fractions. Its origin is not clear, but a derivation from higher grade Variscan basement rocks can be assumed.

The stable heavy minerals zircon, tourmaline, rutile, brookite and anatase are the dominant constituents in rift-related Jurassic sandstone formations of the Lower Austroalpine domain (e.g. Lüdin 1987). They reflect the shallow continental granitic composition of the Variscan basement involved in Jurassic extension and related uplift or exhumation. Their continued occurrence in Cretaceous clastic series indicates that similar Variscan rock series were tectonically imbricated and eroded together with the other, Alpine and Variscan metamorphic series postulated above. In addition, the high stability of these mineral grains during weathering, transport and diagnetic processes may partly imply an origin from older sediments.

From a few Cretaceous clastic series in the NCA, the occurrence of detrital kaersutite (brown amphibole) is known. This is reported from the Cenomanian Walserberg series (associated with chromian spinel and blue amphibole; Miller 1977; Faupl & Miller 1977; Faupl 1984) and from the Valanginian to Barremian, chromian spinel-bearing Rossfeld Formation (e.g. Decker et al. 1987). Kaersutite (formerly syntagmatite) is a frequent constituent in the alkaline ehrwaldite dykes and sills in the Upper Tithonian to Barremian Aptychus Limestone Fm. of the Lechtal nappe (Trommsdorff 1962; Trommsdorff et al. 1990). Hence, the occurrence of detrital kaersutite in the sedimentary series may be explained by the nearby synsedimentary volcanic activity in the palaeogeographic domain from where the NCA were derived. Therefore, for the Rossfeld Fm. it may be suggested that, in addition to the Vardar suture zone (Decker et al. 1987), the volcanic clastic source supplied detrital material to the basin. The reported radiometric ages from the basanitic dykes (ca. 100 Ma) correlate with the sedimentation age of the Walserberg series but are not compatible with the stratigraphic range of the Rossfeld Fm. Possibly, the volcanic activity started earlier. However, from the observed cutting relations of the dykes with the Aptychus Limestone Fm., Trommsdorff et al. (1990) also infer an older Early Cretaceous maximum age.

Supply of the mineral grains

Because of the geodynamic significance, I will mainly discuss the supply of chromian spinel and blue amphibole grains to the various basins. To reconstruct the spatial provenance, it is essential to combine the petrographic data with sedimentological observations. However, it must be borne in mind that multi-phase tectonic deformation and rotation may introduce uncertainities. In the following presentation I refer to examples from which the site of clastic grain input is known from the geometry and lateral facies development (e.g. grain-size trends, continent to shallow sea transitions etc.) recognized on a regional scale, and from sediment transport indicators such as pebble imbrication or sole marks. For a compilation see figures 3 and 4.

Chromian spinel

Earliest, abundant chromian spinel reworking is known from the Valanginian to Barremian Rossfeld Fm. in the NCA. From facies relations, namely the southward deepening of the E-W striking trench-like basin, and from the chemical signature of the spinel grains, a derivation from the Vardar suture zone to the south is inferred (e.g. Decker et al. 1987; Pober & Faupl 1988). With few exceptions, chromian spinel is also present in all Albian to Lower Coniacian clastic series comprised in the Arosa (melange) zone and imbricated Lower Austroalpine units (Lüdin 1987; Winkler 1988, see Fig. 3). Scarce, earlier deposition of detrital chromian spinel is reported from the Arosa zone in sandstone intercalations in the Palombini Shale Fm. (Lüdin 1987) which on lithostratigraphic grounds is tentatively allocated to the pre-Aptian series. Because of the strong tectonic deformation, in the Arosa zone and Lower Austroalpine sandstone formations palaeocurrent data are not reliable. However, in several places their partly Penninic oceanic depositional environment is indicated by the grading up from the ophiolitic basement and sediment series. Characteristically, the sandstones are composed of reworked Penninic oceanic (including Palombini limestone clasts, Lüdin 1987) and Austroalpine continental basement and sedimentary cover clasts. The present detrital composition suggests that the clastic material was derived from a northern Adriatic composite source which was formed during Early Cretaceous convergence between the Penninic oceanic and Adriatic continental plates (e.g. Dietrich & Franz 1976; Winkler 1988; Faupl & Wagreich 1992a).

Chromian spinel is also ubiquitous in the Aptian to Coniacian (Santonian?) Tannheim, Losenstein and Branderfleck Formations in the Walsertal zone, Randzone of the NCA (or "Randcenoman") and in sediments discordantly overlying the Allgäu and external Lechtal nappe series (Fig. 2, 3; e.g. Gaupp 1980, 1982, 1983; Winkler 1988; Faupl & Wagreich 1992a). As discussed below, arguments for a derivation from a northern source (the present North-Adriatic obduction belt) are the same as for the blue amphiboles. Earlier, Barremian occurrences of chromian spinel in the NCA (Randzone and Lechtal nappe) were reported by Hagn (1982) and Winkler (1988). In the Lechtal nappe, chromian spinel is present in turbiditic sandstones intercalated in the Barremian Aptychus Limestone Fm. (Winkler 1988). In the Aptian to Albian (Lower Cenomanian?) Lechtal Kreideschiefer Fm. (Fig. 3) chromian spinel is the dominant heavy mineral species (Winkler 1988). Palaeocurrent data are not available, but generally, the close resemblance of the detrital composition with several sandstone formations in the Arosa zone (Lüdin 1987) and Walsertal zone (Winkler 1988) might suggest a derivation from a northern source (Winkler 1988).

The Upper Turonian to Campanian, Lower Gosau Group formations were deposited in continental to shallow marine basins separated by emergent land areas. Chromian spinel was supplied in variable, but partly significant proportions from sources situated to the north of these basins. This is well constrained by palaeocurrent data and lateral coarsening trends in the occurrences of Brandenberg, Gosau, Weisswasser and Lilienfeld (see Fig. 3, and e.g. Wagreich 1993; Wagreich & Faupl 1994). In several Upper Turonian to Lower Campanian Gosau formations serpentinitic sandstone beds are intercalated. Scarce palaeocurrent data and a southward directed coarsening trend is tentatively interpreted to indicate a derivation from a southern ophiolitic source (Fig. 3 and Wagreich 1993). During the deposition of the Upper Gosau Group formations, from Late Santonian onwards, a considerable NW to SE migrating deepening of the area occurred which led to the deposition of bathyal/abyssal pelagic and turbiditic series from the Late Campanian to the Eocene (Wagreich & Faupl 1994). The resulting northward deepening basins were supplied more and more from southern sources providing mainly metamorphic detritus (garnet, chloritoid etc., but no blue amphiboles) and generally lower amounts of chromian spinel than earlier (see the localities Muttekopf, Gosau, Spitzenbach and Lilienfeld in Fig. 3, e.g. Faupl et al. 1987; Wagreich 1993; Wagreich & Faupl 1994, Ortner 1994). However, chromian spinel is an ultra-stable mineral grain and may undergo several cycles. Its occurrence does not necessarily point to the presence of primary serpentinitic source rocks. For example, chromian spinel grains in the turbiditic Upper Gosau Formations of the Muttekopf area are suggested to be derived from older, eroded chromian spinel-bearing sandstones (Ortner 1994).

Further evidence for a supply of chromian spinel from northern and southern sources comes from chemical data. Based on regional transport indications and related trends in chromian spinel chemistry, Pober & Faupl (1988) postulated a supply of several Upper Gosau Group formations and the Albian Lavant Fm. (comprised in the Drau Range, see Fig. 3) from a Vardar (Tethyan) suture zone to the south. Chromian spinels from other Gosau Group formations, the Cenomanian deep-water Losenstein Fm. of the western NCA and turbiditic sandstones in the Arosa zone and Lower Austroalpine (see Figs. 2, 3) units show a chemical grouping which correlates with a northern provenance (Pober & Faupl 1988). The chromian spinel data from the Branderfleck Fm. (Fig. 2) are not fully compatible with the northern provenance interpretations (Pober & Faupl 1988). However, their close stratigraphical relationship with the Losenstein Fm. and the common occurrence of the other heavy minerals (including blue amphiboles) and rock fragments strongly suggest a northern source provenance (Gaupp 1980, 1983; Winkler 1988).

Blue amphiboles

In the western Eastern Alps detrital blue amphibole (frequently associated with chloritoid, sporadically with lawsonite) is present in the Walsertal zone, in formations of the Randzone and in those coherently overlying the NCA (Fig. 2, 3). In this paper the term Randzone (Kalkalpine Randzone, Winkler 1988) is preferred to the former "Randcenomanzone". The latter term originates from earlier views when a Cenomanian transgression of the sediment series was assumed. In contrast, this sediment series comprises not only Cenomanian, but Albian to Turonian-Coniacian clastic deep-water deposits (Weidich 1984; Winkler 1988). Detrital blue amphiboles are also found in turbidites of the Albian to Coniacian Tannheim, Losenstein and Branderfleck Fms. (Winkler 1988). Microprobe analyses revealed glaucophane, ferroan glaucophane and crossite compositions (Winkler 1988, pers. comm. von Eynatten & Gaupp 1995). The three formations represent a deep-water, pelagic/turbiditic, coarsening upward sequence, prograding from external (Allgäu nappe domain) to internal position (Lechtal nappe domain, Gaupp 1980, 1982, see Fig. 3). During the southward progradation of the Losenstein-Branderfleck system a shallow marine swell developed from Early Turonian onwards along the southern border of the basin, supplying carbonate material to the north (e.g. Oberaudorf ridge, Weidich 1984). The reconstructed regional facies pattern (Gaupp 1980, 1982, 1983) indicates a derivation of the terrigeneous clastic material (including chromian spinel and blue amphiboles) from the north. Further to the east, generally in the northern peripheral part of the NCA, formations similar to the Tannheim-Losenstein and Branderfleck Group can be observed (e.g. Losenstein area, Löcsei 1974; Faupl 1978, 1984; Faupl & Wagreich 1992a, b). In particular, the Cenomanian turbiditic Walserberg Series in the Randzone near Salzburg also contains blue amphiboles with a chemistry similar to that of the mentioned formations (Miller 1977) as well as kaersutite (Faupl 1984).

In conclusion, in the Adriatic domain of the Allgäu and Lechtal nappes during Aptian to Coniacian (Santonian) an E-W trending turbidite basin developed, in which the Tannheim-Losenstein-Branderfleck succession was deposited. It was supplied essentially from a northern source area with terrigeneous clastic material (North-Adriatic obduction belt,

Fig. 3, 4). To the south the basin was bordered by a sheltering carbonate platform and emergent areas (Weidich 1984; Wagreich & Faupl 1994).

Rarely, detrital blue amphiboles are recorded from the Gosau formations. They are present in some of the Coniacian, Lower Santonian and Campanian series in the central and eastern NCA (e.g. Wagreich 1988; Faupl & Wagreich 1992b; Wagreich & Faupl 1994). Facies geometries present in the alluvial and shallow marine series in the Gosau area (Fig. 3) indicate the supply of blue amphiboles from the north and west (Wagreich 1988). In the same locality, during the Early Campanian, a marked change to a southern derivation of the clastic material (without blue amphiole) is documented (Fig. 3 and Wagreich 1988). More data are needed to reveal precisely the supply pattern in other places. Important problems in interpretation may also arise from the definition of Gosau formations. These are considered as sediment series deposited unconformably, after Eoalpine (early Late Cretaceous) deformation, on the Central and Upper Austroalpine nappes (Graz Paleozoic, Gurktal nappe system and NCA). However, the Branderfleck Fm. also shows discordant contacts with the older (often Triassic) sediment series of the NCA (Lechtal nappe). The close spatial and time relations of the Branderfleck Fm. with Gosau deposits is emphasized by Weidich (1984), the Gosau series of the Hieselberg area near Grossraming (Fig. 3) being a good example. In this area reworking of sandstone pebbles and blue amphiboles from underlying Branderfleck sediments into the Coniacian Gosau sediments is documented in detail (Faupl & Wagreich 1992b). Consequently, the provenance of blue amphiboles in Gosau sediments must be tested carefully.

Western Carpathian occurrences of chromian spinel and blue amphiboles

For the present purpose it is important to consider some Carpathian examples (Fig. 1). Like in the Alps, Cretaceous siliciclastic formations of the Western Carpathians contain considerable amounts of chromian spinel. Chromian spinel is found in Aptian/Albian and Upper Cretaceous clastic formations in the Tatric and Fatric (Krizna) units (e.g. Misik in Rakus et al. 1990) which represent Adriatic domains in the Carpathian chain equivalent to these in the Alpine domain. Across the Vienna basin, the Cretaceous palaeogeographic domains of the easternmost NCA and the Inner Carpathians can be correlated on the basis of similar Gosau formations in the Brezovské Karpaty Mountains (Fig. 1, 4). Chromian spinel is a major constituent in the present heavy mineral associations (also bearing scarce chloritoid and blue amphibole) of the Upper Coniacian to Paleocene series and the provenance from a northern source situated between the Penninic and Adriatic domains is inferred (Wagreich & Marschalko 1995).

Ophiolitic pebbles and/or chromian spinel mineral grains are also present in the Slowakian, Albian to Cenomanian parts of the Manin and Klape units (Fig. 1, Misik & Marschalko 1988). However, their precise palaeogeographic position with respect to the source area (the "exotic" ridge, Fig. 4) is not clear. Generally, the existence of an ophiolitic source is related to the closure of the Pieniny-Meliata ocean (e.g. Birkenmajer 1986; Rakus et al. 1990). In the Western Carpathians of Poland chromian spinel mineral grains occur in Upper Cretaceous sediments of the northern Pieniny basin, thus pointing to the emergence of ophiolite-bearing sources during similar times as in the Alpine domain (Fig. 4; and Winkler & Slaczka 1994).

The Albian deep-marine conglomerates of the Klape unit are also known to contain detrital blueschist clasts (Marschalko 1986) and blue amphibole mineral grains (Winkler & Slaczka 1994). Preliminary dating of such blueschist pebbles revealed three K/Ar whole rock ages of ca. 150–160 Ma (pers. comm. P. Stille 1994) and Ar/Ar phengite ages of 155.4 ± 0.6 Ma (Dal Piaz et al. 1995). These age interpretations would point to an older, Jurassic subduction and blueschist metamorphic event (Dal Piaz et al. 1995). The palaeogeographic position of the basin is difficult to interprete, because palaeocurrent data indicate a basin parallel transport from E/SE to W/NW (Marschalko 1986). Partly a position of the basin in the Pieniny ocean in front or to the N or NW of the supplying ridge is inferred (Rakus et al. 1990, see also Fig. 4). According to Birkenmajer (1986) the Klape basin may have been situated on the Adriatic plate to the south of the supplying "exotic" ridge. On the other hand, a position of the basin on the Adriatic plate and a supply from the Meliata zone to the SE (Fig. 1, 4) also may be suggested. In spite of the similar timing with respect to the deposition of ophiolitic and blueschist clastic material in the Eastern Alps and Carpathians, the radiometric age of the blueschist pebbles in the Western Carpathians would point to Late Jurassic (time scale of Harland et al. 1990) subduction and metamorphism in the Carpathians (Dal Piaz et al. 1995). According to current palaeotectonic models, in the Eastern Alps this period is not correlated with important convergent movements along the Penninic-Adriatic margin.

Summary

In the Austroalpine (Adriatic) and Penninic domains of the Eastern Alps reworking of chromian spinel is recorded from the Valanginian (Rossfeld Fm.) and Barremian (Arosa zone, Randzone, Allgäu und Lechtal nappes) on. Detrital blue amphiboles appear from the Albian onwards in clastic sediments which are preserved in the Randzone, Walsertal zone and NCA. The spatial relations of the basins with the hypothetical source areas are summarized in Fig. 4.

For the Penninic Arosa zone, Lower Austroalpine, the Walsertal zone and the Randzone of the NCA, a derivation of the clastic material from mixed, uplifted oceanic/continental sources appears well constrained. They supposedly formed an elongated belt (North-Adriatic obduction belt) along the northern Adriatic margin and supplied sedimentary basins situated in the Penninic and Austroalpine domains. During Aptian to Coniacian, in the external (in particular the NW) part of the Austroalpine domain a deep-sea basin with turbiditic and mass flow sedimentation developed (Tannheim-Losenstein-Branderfleck system) which also received detritus from the emerged belt to the north (Fig. 4). The supplying belt was composed of a variety of continental and oceanic basement and sedimentary cover series and, in addition, of blueschist rocks. Blueschist metamorphic detritus appears from the Middle Albian onward. The depositional axis of the elongated basin migrated south/southeastward in time (Fig. 3). The basin extended probably far to the east and was bordered along its southern side by productive carbonate ridges and emergent land areas. The southeastward prograding trend in the Tannheim-Losenstein-Branderfleck sedimentary system and the emergence along its southern margin, supposedly reflects a foreland basin evolution in front of the southward advancing and supplying northern belt (Fig. 4). From Late Coniacian/Santonian on, the emergent area was increasingly occupied by continental and shallow marine basins (Lower Gosau Group) which still were partly supplied from northern source areas. Subsequent Santonian to Campanian deepening of the Gosau basins is paralleled by increasing supply from a southern source (Vardar suture zone, Fig. 4). The input from the northern belt supposedly ceased during the Coniacian/Santonian. Continued deepening resulted in north-sloping bathyal/abyssal basins receiving the turbiditic Upper Gosau Group sediments supplied from a southern source.

The Late Santonian to Maastrichtian Central Alpine Gosau of Styria represents a special case. Contrary to the Gosau formations in the NCA it was not supplied with ophiolitic detritus (e.g. chromian spinel, Fig. 3). Pebble analysis in conglomerates suggest a derivation of the clastic material from South Alpine sediment series (Gollner et al. 1987). Hence, the Styrian Gosau series do not provide information about the palinspastic position of the Vardar suture zone.

From the spatial occurrence of the chromian spinel and blue amphibole detrital minerals (Fig. 4) it clearly appears that grains derived from blueschist metamorphic terranes are restricted to the sedimentary series connected with the northern source, whereas, chromian spinel is supplied from the northern and southern sources. The southern source is assumed to reflect ophiolite obduction during the closing of the Vardar oceanic domain since the Jurassic (Pober & Faupl 1988; Faupl & Wagreich 1992a, Wagreich & Faupl 1993). From the present palaeotransport and petrographic data this suture zone does not appear to have supplied blueschist metamorphic minerals to the Austroalpine domain. A similar paleogeographic pattern may be postulated for the Western Carpathian area (Fig. 1, 4). After common palinspastic reconstructions, the Klape basin was probably situated to the north of the supplying ridge (Fig. 4 and Rakus et al. 1990). However, a position to the south of the exotic ridge and detrital input from the Meliata suture zone also appears possible. Indeed, a similar timing of reworking of ophiolitic and blueschist metamorphic rocks in the Western Carpathian and Austroalpine domains is observed. From sedimentological evidence, Alpine convergence-related blueschist metamorphic terrains would have been included in a belt bordering the Adriatic margin to the north. The possible processes for the formation of this composite structure in the western part of the Austroalpine domain is the topic of the next section.

Subduction versus obduction

As argued above, the history of the northwestern Adriatic margin is characterized by the Early Cretaceous appearance of a northern sediment source bearing ophiolitic and blueschist metamorphic series. This reflects the uplift of considerable volumes of oceanic basement and blueschist metamorphics. However, these oceanic and metamorphic complexes are no longer preserved. Therefore, only indirect evidence and comparisons with preserved examples can be used to explain their generation.

Ancient and modern oceanic subduction and uplift of oceanic crust at convergent margins typically is accompanied by important continental or oceanic volcanic arc formation (e.g. Searle & Stevens 1984). At the Cretaceous Penninic-Adriatic margin no subduction-related calc-alkaline volcanism appears to have developed. On the contrary, Early Cretaceous extension in the continental margin gave way to dyke and sill intrusions derived from a sub-continental mantle source (Trommsdorf et al. 1990). Taking into account the crustal dimension indicated by these volcanic processes, the extensional process must have been of regional importance. These arguments suggest that subduction may not have played a major role in the uplift of ophiolitic rocks and in the formation of the North-Adriatic source terrain.

Continued oceanic subduction may give rise to ordered accretionary prism formation which means the regular oceanward stratigraphic younging of successively accreted sediment packages or imbricates. In several works (e.g. Dietrich & Franz 1976; Stampfli 1993; Wagreich & Faupl 1994) the formation of a Cretaceous subduction-related accretionary prism along the Penninic-Austroalpine margin is suggested. This opinion is not shared by Lüdin (1987) and Winkler (1988), because of the lack of positive evidence for it in the marginal domains of the Adriatic margin, in the Arosa zone and Walsertal zone. There, from stratigraphical and lithological evidences one major, short-lived imbrication and melange formation period can be inferred (Late Coniacian to? Early Santonian). Also the reconstruction of relative motions of the NCA nappes in Winkler (1988, using plate path data of Savostin et al. 1986) does not suggest a continuous northward movement of the Adriatic margin during the Cretaceous. A rapid northward movement of Adria can be assumed for the period from 130 to 110 Ma (corresponding approximately to the Barremian to Early Albian stages, Harland et al. 1990). From 110 to 80 Ma (ca. Late Albian to Early Campanian) left lateral transpressive movement with minor convergence should have occurred between the Adriatic and Penninic realms. Major S-N oriented convergence started only during Late Campanian and lasted until the collision with the European margin in the Eocene (see also Fig. 19 in Winkler 1988). This suggests that Late Coniacian to Early Santonian melange formation and tectonic imbrication in the Arosa and Walsertal zones occurred during transpressive movements along the Penninic-Adriatic margin. The age of the youngest (Turonian-Early Coniacian) elements in these melange zones brackets the melange formation event from the Late Coniacian to Early Santonian and the later reactivation in the Late Eocene, when they were remobilized during the main Alpine thrusting (see Fig. 6 and discussion below).

If it is accepted that continued subduction and accretion was not the driving mechanism for the uplift of ophiolite and blueschist metamorphic rocks along the northern Adriatic margin, the current corner flow models (Cowan & Silling 1978; Cloos 1982) or the orogenic wedge model of Platt (1986) do not apply. This can be demonstrated, because both models demand high subduction rates over tens of millions of years. Consequently, in the areas where the models were established, significant subduction-induced volcanism developed in the overriding continental plate. On the other hand, simple oceanic subduction as prevailing for example along the western South American margin is not an efficient mechanism in order to drive important accretion or obduction and uplift of oceanic crust (Dalziel & Forsythe 1985). Terrane collision may be considered to represent an efficient mechanism for obduction and uplift of oceanic crust. Terranes essentially may consist of far travelled fragments of continental crust, intra-oceanic volcanic arcs, or detached fragments of the continental margin which were re-welded during later convergene (Howell 1989). It appears possible that during Jurassic-Early Cretaceous asymmetric extension at the Adriatic margin distal blocks were separated. The formation of such extensional allochthons at the Adriatic margin has been suggested earlier (e.g. Trommsdorff et al. 1993, Manatschal 1995; Froitzheim & Manatschal, in press). During consequent Cretaceous convergence they became amalgamated with the main Adriatic continental plate. Possibly, at the same time extension-related buoyant intervening oceanic lithosphere could have been obducted onto the cool Adriatic margin.

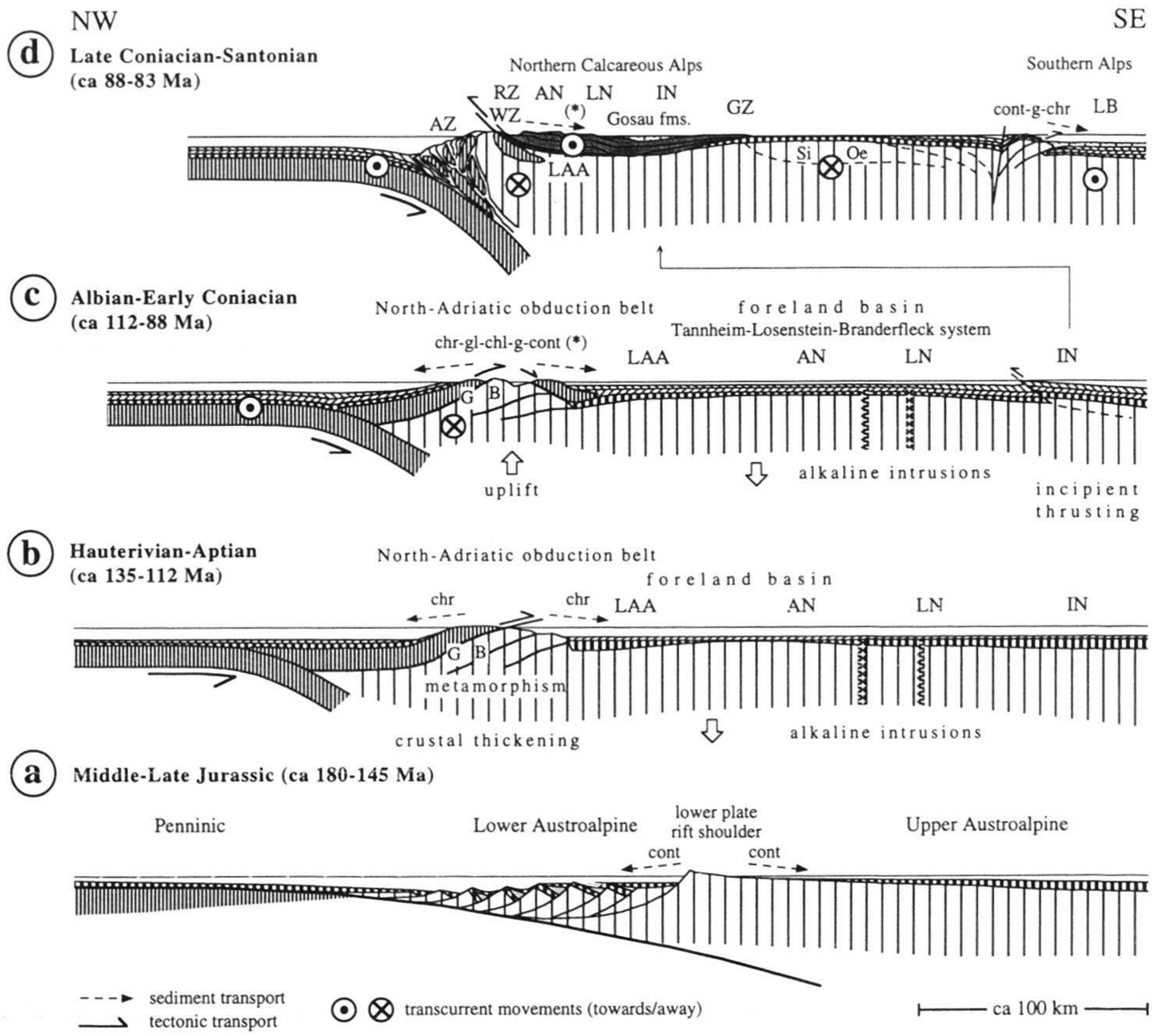

Fig. 5. Interpreted Jurassic to Createaceous palinspastic sections including informations extrapolated from the western part of the Eastern Alps. The trace of the sections is indicated in Fig. 3. The possible presence of extensional allochthones is ignored. Vertical exaggeration of the thickness of sediment series is admitted. Numerical ages are from Harland et al. (1990). Key to tectono-stratigraphic units: AN = Allgäu nappe, AZ = Arosa zone, GZ = Grauwacke zone, IN = Inntal nappe, LAA = Lower Austroalpine nappes, LB = Lombardian basin, LN = Lechtal nappe, Oe = Oetztal nappe, Si = Silvretta nappe, WZ = Walsertal zone. B and G indicate hypothetical sites of Alpine blueschist and greenschist metamorphism. Key to heavy minerals: chl = chloritoid, cont = zircon, tourmaline, apatite, rutile and other titanoferous minerals, chr = chromian spinel, g = garnet, gl = glaucophane plus traces of lawsonite.

The lack of evidence for long lasting subduction at the northern Adriatic margin suggests that primarily the obduction of oceanic lithosphere could have been responsible for ophiolite and blueschist rock uplift and erosion. Two alternative models are available to explain the uplift of oceanic and blueschist terranes in obduction regimes. Firstly, preceding intra-oceanic subduction governed blueschist metamorphism and the resulting rocks were transported and obducted onto the continental margin (as supposed for Papua New Guinea, Pieters 1978; Davies & Jaques 1984), or, secondly, blueschist metamorphism occurred in the overthrusted cool continental plate during the obduction of an oceanic slab

(Oman model, e.g. Gealey 1977; Lippard et al. 1986; Robertson & Searle 1990; Le Métour et al. 1990). Concerning the latter model it may be argued that probably the necessary pressure conditions were not reached. However, it is known that metamorphic glaucophane/lawsonite formation can occur at relatively shallow depth, if the available chemistry of the protoliths is favourable. Generally, carbonate-bearing rocks and basalts have a suitable chemical composition (Oberhänsli 1986).

Along the Oman margin (see e.g. Lippard et al. 1986; Robertson & Searle 1990; Le Métour et al. 1990) during the Campanian a young oceanic slab (Semail ophiolite, approximately 10 km thick, about 1000 km long and 100 km wide) was thrusted over the distal, thinned Arabian continental margin. In the overthrusted, cool continental basement and sedimentary cover blueschist metamorphism occurred. Greenschist metamorphism took place in warmer levels above. Tectonic thickening of the crustal portion induced uplift and exhumation of the continental basement and the metamorphics. Obduction and uplift are reported to have occurred during a time span of about 20 Ma (Lippard et al. 1986). In front of the obducted and uplifted Semail ophiolite a deepening marine foreland basin formed (Suneinah foredeep) which was increasingly supplied by the uplifting allochthonous complex (Fiqa and Juweiza Fms., Boote et al. 1990; Robertson & Searle 1990). A theoretical succession of heavy minerals in basins adjacent to such an obducted slab would be such that at first ophilitic mineral grains appear and later on, continental basement and related metamorphic material.

A similar mineral succession is observed along the Early Cretaceous western Adriatic margin. Pre-Aptian siliceous limestones in the Arosa zone (Lüdin 1987), Barremian limestones of the Lechtal nappe and Randzone of the NCA (Hagn 1982; Winkler 1988) contain turbidite intercalations with chromian spinel dominating the heavy mineral fraction. Mixed ophiolitic, continental basement and Alpine blueschist material was supplied later, from the middle Albian on to various western Adriatic margin series (see Fig. 4). Ophiolite obduction along the Adriatic margin and related thickening of the crust could have caused down-bending and extension in the distal Adriatic lithosphere giving way for basanitic dyke intrusion and extrusion (Trommsdorff et al. 1990). In summary, the obduction scenario of Oman as interpreted from preserved outcrops, may serve as a model for the Cretaceous northwestern Adriatic margin. The implied geographical dimension, sedimentation pattern and time requirement are all compatible. The Barremian to Early Albian convergence along the Penninic-Adriatic margin, as reconstructed from general plate movements (Savostin et al. 1986; Winkler 1988) matches well the constraints of the sedimentary record. The Oman-type obduction is a model for several other ancient and modern convergent margins. One analogue may be found in the Brooks Range of Arctic Alaska where (Oman-type) obduction of an ophiolitic complex is inferred to have triggered blueschist and greenschist metamorphism (Harris 1992). The resulting metamorphic core supplied detrital glaucophane, chloritoid and garnet to the adjacent Albian foreland basin fill series to the north (Till 1992).

A model for the western part of the Eastern Alps

During the Middle to Late Jurassic, extension occurred along the Adriatic margin. Probable asymmetrical extension may have given rise to the formation of a lower plate rift shoulder in the "Middle" Austroalpine (sensu Tollmann 1977) domain (Fig. 5a). Different interpretations of upper/lower plate geometries at the Adriatic margin are proposed by Froitzheim & Eberli (1990), Trommsdorff et al. (1993), Manatschal (1995) and Froitzheim & Manatschal (in press). The observed fault geometries suggest that the Adriatic domain represented a lower plate margin (Froitzheim & Eberli 1990; Manatschal 1995 and Froitzheim & Manatschal in press). During the breakaway a rift shoulder formed which is manifested in the coeval sediment record. The products of uplifted and exposed shallow continental basement and sedimentary cover are known from the widespread Lower Austroalpine, Middle Jurassic turbiditic deposits (e.g. Saluver Fm., Fig. 5a). The probable formation of extensional allochthons is neglected here for the purpose of simplicity.

The interpretation of the subsequent convergence-related processes is hypothetical (Fig. 5b–d). However, there are two main points to be considered which are in line with an earlier asymmetric extensional development. Firstly, the Cretaceous convergence along the Adriatic margin does not appear to be driven by oceanic crust accretion in the Penninic realm, but mainly by the relative northern displacement of the Adriatic continent with respect to the Penninic and Eurasian domains (Savostin et al. 1986), and secondly, close to the distal Adriatic margin buoyant oceanic lithosphere could have been inherited from asymmetric extension (sensu Wernicke 1985). Generally, these conditions may have governed solely the obduction of an oceanic slab (or serpeninite ridge, Winkler 1988) on the distal Adriatic margin. Alternatively, during the earliest Cretaceous an intra-Penninic subduction regime could have been established which was probably driven by the opening of the North Penninic branch in the Western Alpine domain (Stampfli 1993; Steinmann 1994). The presence and orientation of such a subduction zone is speculative. However, for subsequent Late Coniacian-Santonian thrusting and melange formation (Fig. 5d) an incipient southward-dipping oblique subduction may be plausibly inferred.

To satisfy the time constraints implied by the occurrence of volcanic activity and by the appearance of detrital chromian spinel grains in the sedimentary record, a Hauterivian to Aptian obduction (Fig. 5b) of an oceanic slab on the distal Adriatic margin may be suggested. Resulting loading and down-bending of the Adriatic crust would have forced extension and rising of basanitic sub-continental magmas as described by Trommsdorff et al. (1990). Consequent emergence of the oceanic slab is documented by the intercalation of chromian spinel bearing turbidites into coeval Barremian and (?) older pelagic carbonate sediments deposited on the continental and oceanic side (NCA and Arosa zone) of the obduction belt. Blueschist metamorphism could have occurred in the overthrusted continental margin basement and sediment series (Fig. 5b). Greenschist and amphibolite-grade metamorphism, as indicated by later reworking of chloritoid, garnet, epidote and minor amounts of green hornblende, may probably be attributed to the presence of a metamorphic sole at the base of the obducted slab. Due to loading exerted by the obduction complex on the continental side of the slab (Fig. 5b, c) a foreland basin was formed which represented the depositional sites of the Albian to Coniacian Tannheim-Losenstein-Branderfleck system. Foreland bulge uplift in the Lechtal nappe domain may have caused the establishment of small shallow-water carbonate shelves and emerged land areas bordering the terrigeneous clastic domain to the south.

Obduction related thickening (or flexural relaxation) of the distal continental margin induced rapid isostatic uplift and exhumation of continental basement and metamorphics

(Fig. 5c) as indicated by the detrital grains in Albian to Coniacian continental margin foreland series (Tannheim-Losenstein-Branderfleck prograding system). Regional south facing relief and/or simply asymmetrical occurrence of the exhumed blueschist series may have controlled reworking of the metamorphic detritus towards the foreland basin to the south. Clastic series on the oceanic side, now preserved in the Arosa zone, were supplied with ophiolitic and continental margin basement grains.

The youngest Turonian to Early Coniacian stratigraphic age of clastic sediments comprised in the Arosa and Walsertal zones suggests that transpressive melange formation and tectonic imbrication occurred during the Late Coniacian to Early Santonian (Fig. 5d). For this period several radiometric cooling age data are available, documenting earlier deformation and metamorphism in the Austroalpine basement and cover (ca. 100-80 Ma, Thöni 1980, 1982, 1983, 1986) which are correlated with the pre-Gosauian deformation event (e.g. Frank 1987). The formation of the melanges and nappe imbrication can be correlated with the Trupchun phase of Froitzheim et al. (1994). Related Late Coniacian to Santonian W/NW directed thrusting (e.g. Ratschbacher 1986; Ring et al. 1988; Froitzheim et al. 1994) in the Austroalpine domain may have been governed by the eastward movement of the Adriatic plate from 110-80 Ma (Winkler 1988 following Savostin et al. 1986). This process would have induced shortening in the eastern Alpine and Carpathian domains and subsequent deformation propagation (extrusion) towards the west along a sinistral wrench zone as suggested by Froitzheim et al. (1994). During this period the thrusting and emplacement of the NCA nappes in front of the Silvretta/Oetztal units may have occurred.

In this regard, different views of the palaeogeographical derivation of the NCA must be discussed. Based on facies correlations, Tollmann (1977) proposed a derivation of these nappes from south of the Oetztal/Silvretta basement complexes. However, on grounds of tectonic relations of the Phyllitgneis zone and the NCA with the Silvretta nappe (Fig. 2), and oblique metamorphic zoning in the Oetztal basement, Frank (1987) demonstrates that the NCA were not thrusted over the Oetztal/Silvretta nappes. Their actual tectonic relations suggest that the NCA domain was situated to the north of the basement complexes, because the latter occupy a higher structural position (Frank 1987) with respect to the former. However, the Coniacian to Santonian westward thrusting of the NCA (Fig. 5d), as proposed here, could have transported the NCA nappe pile in front of the Silvretta/Oetztal basement. Actual N-S oriented sections do not represent the original palinspastic arrangement of the concerned palaeogeographic domains. The observed overthrusting of the NCA by the Silvretta/Oetztal basement nappes could have occurred during later (Tertiary) northward movements. The present model conceives an original, approximatively W-E arrangement of the Silvretta/Oetztal basement and the NCA domains, and it is in line with a peripheral northern Adriatic position of the NCA domains as implied from structural (Frank 1987) and sedimentary arguments (Gaupp 1982, 1983; Winkler 1988).

The above discussed westward thrusting of the NCA has driven melange formation and imbrication present in the Walsertal zone and in the Randzone (Fig. 5d). Oblique convergence along the Penninic-Adriatic border zone also induced melange formation and imbrication in the Arosa zone (Fig. 5d). The lithological content and inferred palaeotectonic position of the Walsertal zone is different from the Arosa zone (Winkler 1988). However, their similar stratigraphical range suggests their coeval formation. At the tran-

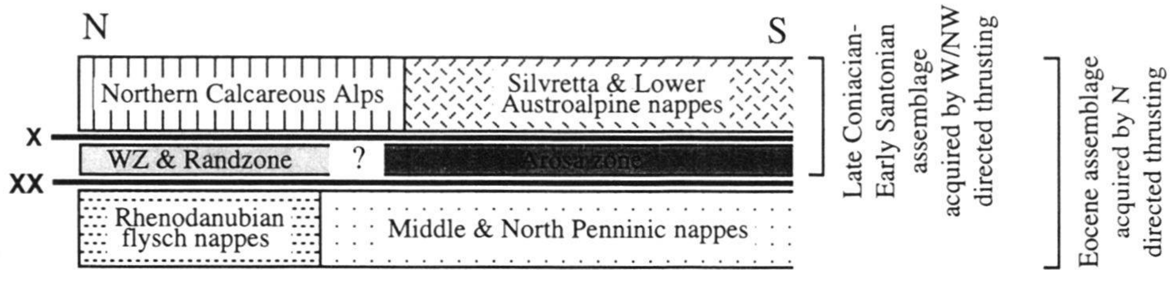

Fig. 6. Schematic presentation of the tectonic position of the western Austroalpine (Adriatic) margin units, acquired during an earlier Late Cretaceous and the Tertiary main thrusting events. The Walsertal zone and Randzone (imbricate zone) are sandwiched between the Northern Calcareous Alps and the Penninic Rhenodanubian nappe (comprising youngest series from Maastrichtian up to the Eocene). The Arosa zone typically occupies a position between the Austroalpine basement and Lower Austroalpine nappes above and the Middle and North Penninic units of the Western Alps below (see also Fig. 2).

sition between the Austroalpine and South Alpine domains Late Cretaceous sinistral transpressive deformation is inferred by Schuhmacher et al. (in press). According to these authors, south verging folding and thrusting (Fig. 5d) triggered the uplift of high-grade metamorphic basement and overlying sedimentary cover which was reworked into the Lombardian (flysch) basin (Bernoulli & Winkler 1990).

The nappe emplacement of the NCA coincides with the start of the continental and shallow marine Lower Gosau series (see Fig. 5d and Flügel et al. 1987). These series were first supplied from remnants of the obduction belt and uplifted NCA series to the north (e.g. Faupl & Wagreich 1992). Farther to the east, the southern source of the Vardar suture zone also became more important with time. The existence of the Vardar suture zone is inferred by Faupl & Wagreich (1992) from Cretaceous eclogite metamorphism in the Austroalpine basement (Koralpe and Saualpe, see Fig. 3 and Thöni & Jagoutz 1992). However, recording a last thermal climax at around 90 Ma (Thöni & Jagoutz 1992) these series could not have supplied high-P/low-T metamorphic grains to the sediment basins discussed here. Other radiometric age data from Upper Austroalpine Palaeozoic and Mesozoic sediments in that area (Neubauer et al. 1987; Frank et al. 1987; Fritz 1988) point to deformation and cooling at ca. 140-130 Ma. Generally, these radiometric age data may be correlated with the Early Cretaceous tectonic event during which the North-Adriatic obduction belt formed.

The presently proposed situation, reached during the Late Coniacian and Early Santonian was modified during the latest Cretaceous (from 90 Ma on) to Eocene development of the Austroalpine margin. Northward movement of the Adriatic margin units caused the block (consisting of the NCA nappes and underlying Walsertal zone and Randzone, Austroalpine basement and sedimentary nappes and Arosa zone) to be thrust over external North and Middle Penninic units which contain sediments as young as Early Eocene (Fig. 6). The different sites of formation of the Arosa zone and Walsertal zone as depicted here (Fig. 5) and their final, different structural position (Fig. 6) proves the individuality of each of these units.

Conclusion

The Cretaceous sedimentary record along the Penninic-Adriatic continental margin provides information about surface processes which are thought to reflect deep-seated crustal dynamics. The convergence-related clastic sediment series of the Austroalpine realm were supplied from the North-Adriatic obduction belt to the north and from the Vardar suture zone to the south. Blueschist metamorphic grains were supplied solely from the North-Adriatic obduction belt.

For the early to early Late Cretaceous history of the northern Adriatic margin, a model is developed which proposes a southward obduction of Penninic oceanic crust and related blueschist metamorphism. The model is based on the nature of detrital grains in the sedimentary formations, their supply in space and time and the assumption of an Alpine metamorphic formation of blueschists. Conclusive answers will be available only when the blue amphibole grains have been dated adequately. The lack of calc-alkaline volcanism and long lasting formation of ordered accretionary prisms supports the proposed ophiolite obduction model and excludes continuous Cretaceous subduction of South Penninic crust under the Adriatic margin as a driving mechanism of blueschist metamorphism.

The Late Cretaceous history of the Adriatic margin is in good agreement with several data derived from structural and geochronological work in the Austroalpine units. The supposed Early Cretaceous history of the northern Adriatic margin, however, is documented only scantily by geochronological and structural data. These will probably remain difficult to prove, because the uplifted basement and sedimentary complexes, recognized as sources of coeval clastic sediments have been partly eroded. In addition, latest Cretaceous and Tertiary subduction should have triggered their deep burial under the northward thrusted Austroalpine units.

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REFERENCES

Bernoulli, D. & Weissert, H. 1985: Sedimentary fabrics in Alpine ophicalcites, South Pennine Arosa zone, Switzerland. Geology 13, 755–758.

Bernoulli, D. & Winkler, W. (1990): Heavy mineral assemblages from Upper Cretaceous South- and Austroalpine flysch sequences (Northern Italy and Southern Switzerland): source terranes and palaeotectonic implications. Eclogae Geol. Helv. 83, 287–310.

Birkenmajer, K. 1986: Stages of structural evolution of the Pieniny klippen belt, Carpathians. Studia Geol. Polonica 88, 7–32.

Cloos, M. 1982: Flow melanges: Numerical modelling and geologic constraints on their origin in the Franciscan subduction complex, California. Bull. Geol. Soc. Amer. 93, 330–345.

Cowan, D.S. & Silling, R.M. 1978: A dynamic scaled model of accretion at trenches and its implications for the tectonic evolution of subduction complexes. J. Geophys. Res. 83/B11, 5389–5396.

DAL PIAZ, G.V., MARTIN, S., VILLA, I.M., GOSSO, G. & MARSCHALKO, R. 1995: Late Jurassic blueschist pebbles from the Western Carpathian orogenic wedge and paleostructural implications for Western Tethys evolution. Tectonics (in press).

DAVIES, H.L. & JAQUES, A.L. 1984: Emplacement of ophiolite in Papua New Guinea. In: Ophiolites and oceanic lithosphere. (Ed. by GASS, I.G., LIPPARD, S.J. & SHELTON, A.W.) Geol. Soc. London Spec. Publ. 13, 341–349.

DECKER, K., FAUPL, P. & MÜLLER, A. 1987: Synorogenic sedimentation on the Northern Calcareous Alps during the Early Cretaceous. In: Geodynamics of the Eastern Alps. (Ed. by FLÜGEL, H.W. & FAUPL, P.) Deuticke, Vienna, 126–141.

DERCOURT, J., RICOU, J.L., ADAMIA, S., CSASZAR, G., FUNK, H., LEFELD, J., RAKUS, M., SANDULESCU, M., TOLLMANN, A. & TCHOUMACHENKO, P. 1990: Anisian to Oligocene paleogeography of the European margin of Tethys (Geneva to Baku). Mém. Soc. Géol. France N.S. 154 (III, pt. 1), 159–190.

DIETRICH, V.J. & FRANZ, U. 1976: Alpidische Gebirgsbildung in den Ostalpen: ein plattentektonisches Modell (Kurzfassung). Geol. Rdsch. 65, 361–374.

FAUPL, P. 1978: Zur räumlichen und zeitlichen Entwicklung von Breccien- und Turbiditserien in den Ostalpen. Mitt. Ges. Geol. Bergbaustud. Österr. 25, 81–110.

– 1983: Die Flyschfazies in der Gosau der Weyerer Bögen (Oberkreide, Nördliche Kalkalpen, Österreich). Jb. Geol. B.-A., Wien 126, 219–244.

– 1984: Ein Beitrag zur Kenntnis der Walserberg-Serie bei Salzburg. Mitt. österr. geol. Ges. 77, 33–36.

FAUPL, P. & MILLER, CHR. 1977: Über das Auftreten von Kaersutit als Schwermineral in den Rossfeldschichten (Unterkreide) der Nördlichen Kalkalpen. Anz. Österr. Akad. Wiss., math.-naturwiss. Kl., 1977, 156–160.

FAUPL, P. & WAGREICH, M. 1992a: Cretaceous flysch and pelagic sequences of the Eastern Alps: correlations, heavy minerals, and palaeogeographic implications. Cretaceous Res. 13, 387–403.

FAUPL, P. & WAGREICH, M. 1992b: Transgressive Gosau (Coniac) auf Branderfleckschichten (Turon) in den Weyerer Bögen (Nördliche Kalkalpen, Oberösterreich). Jb. Geol. B.-A., Wien 135, 481–491.

FAUPL, P., POBER, E. & WAGREICH, M. 1987: Facies development of the Gosau Group of the eastern parts of the Northern Calcareous Alps during the Cretaceous and Paleogene. In: Geodynamics of the Eastern Alps. (Ed. by FLÜGEL, H.W. & FAUPL, P.) Deuticke, Vienna, 142–155.

FLÜGEL, H.W., FAUPL, P. & MAURITSCH, H.J. 1987: Implications on the Alpidic Evolution of the eastern parts of the Eastern Alps. In: Geodynamics of the Eastern Alps. (Ed. by FLÜGEL, H.W. & FAUPL, P.) Deuticke, Vienna, 407–414.

FRANK, W. 1987: Evolution of the Austroalpine elements in the Cretaceous. In: Geodynamics of the Eastern Alps. (Ed. by FLÜGEL, H.W. & FAUPL, P.) Deuticke, Vienna, 379–406.

FRANK, W., KRALIK, M., SCHARBERT, S. & THÖNI, M. 1987: Geochronological data from the Eastern Alps. In: Geodynamics of the Eastern Alps. (Ed. by FLÜGEL, H.W. & FAUPL, P.) Deuticke, Vienna, 272–281.

FRITZ, H. 1988: Kinematics and geochronology of Early Cretaceous thrusting in the northwestern Paleozoic of Graz. Geodin. Acta 2, 53–62.

FROITZHEIM, N. & EBERLI, G.P. 1990: Extensional detachment faulting in the evolution of a Tethys passive continental margin, Eastern Alps, Switzerland. Bull. Geol. Soc. America 102, 1297–1308.

FROITZHEIM, N. & MANATSCHAL, G. in press: Kinematic model for Jurassic rifting, mantle exhumation, and passiv-margin formation in the Austroalpine and Penninic nappes (Eastern Switzerland). Bull. Geol. Soc. Am.

FROITZHEIM, N., SCHMID, ST. M. & CONTI, P. 1994: Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. Eclogae geol. Helv. 87, 559–612.

GAUPP, R.H. 1980: Sedimentpetrographische und stratigraphische Untersuchungen in den oberostalpinen Mittelkreide-Serien des Westteils der Nördlichen Kalkalpen. Diss. Techn. Univ. München.

– 1982: Sedimentationsgeschichte und Paläotektonik der kalkalpinen Mittelkreide (Allgäu, Tirol, Vorarlberg). Zitteliana 8, 33–72.

– 1983: Die paläogeographische Bedeutung der Konglomerate in den Losensteiner Schichten (Alb, Nördliche Kalkalpen). Zitteliana 10, 155–171.

GEALEY, W.K. 1977: Ophiolite obduction and geologic evolution of the Oman Mountains and adjacent areas. Geol. Soc. Amer. Bull. 88, 1183–1191.

GOLLNER, H., SCHIRNIK, D. & TSCHELAUT, W. 1987: The problem of the Southalpine clasts in the "Mittelsteirische Gosau". In: Geodynamics of the Eastern Alps. (Ed. by FLÜGEL, H.W. & FAUPL, P.) Deuticke, Vienna, 156–163.

HÄUSLER, H. 1988: Unterostalpine Jurabreccien in Österreich: Versuch einer sedimentologischen und paläogeographischen Analyse nachtriadischer Breccienserien im unterostalpinen Rahmen des Tauernfensters (Salzburg–Tirol). Jb. Geol. B.-A. 131, 21–125.

HAGN, H. 1982: Neue Beobachtungen in der Unterkreide der Nördlichen Kalkalpen (Thierseer Mulde SE Landl, Kalkalpine Randschuppe SW Bad Wiessee). Mitt. bayer. Staatssamml. Paläont. Hist. Geol. 22, 117–135.

HARLAND, W.B., ARMSTRONG, R.L., COX, A.V., CRAIG, L.E., SMITH, A.G. & SMITH, D.G. 1990: A geologic time scale in 1989: Cambridge University Press.

HARRIS, R.A. 1992: Pre-collisional extension and the formation of Oman-type ophiolites in the Banda arc and Brooks range. In: Ophiolites and their modern oceanic analogues. (Ed. by PARSON, L.M., MURTON, B.J. & BROWNING, P.) Geol. Soc. London Spec. Publ. 60, 301–325.

HOWELL, D.G. 1989: Tectonics of suspect terranes. Chapman and Hall, London, New York.

LIPPARD, S.J., SHELTON, A.W. & GASS, I.G. 1986 (Ed.): The ophiolite of northern Oman. Mem. Geol. Soc. London 11.

LÖZCEI, J. 1974: Die geröllführende mittlere Kreide der südlichen Kalkvoralpen. Jb. Geol. B.-A., Wien 117, 17–54.

LÜDIN, P. 1987: Flysch- und Melangebildungen in der südpenninisch/ostalpinen Arosa-Zone (Mittelbünden und Rätikon, Schweiz). PhD thesis Univ. Basel.

MANATSCHAL, G. 1995: Jurassic rifting of a passive continental margin (Platta and Err nappes, Eastern Switzerland): geometry, kinematics and geochemistry of fault rocks and a comparison with the Galicia margin. PhD thesis ETH-Zürich.

MARSCHALKO, R. 1986: Evolution and geotectonic significance of the Klippen Belt Cretaceous flysch in the Carpathian megastructure. VEDA, Bratislava.

MILLER, CHR. 1977: Detrital ferroglaucophane from the Cenomanian Walserberg series, Salzburg, Austria. N. Jb. Mineral. Mh. 12, 544–547.

MISIK, M. & MARSCHALKO, R. 1988: Exotic conglomerates in flysch sequences: Examples from the West Carpathians. Mém. Soc. Géol. France N.S. 154, 95–113.

NEUBAUER, F., FRISCH, W. & HANSEN, B.T. 1987: Time relations between Eoalpine metamorphism and thrusting: Evidence from crystalline basement of the eastern Greywacke Zone. In: Geodynamics of the Eastern Alps. (Ed. by FLÜGEL, H.W. & FAUPL, P.) Deuticke, Vienna, 263–271.

OBERHÄNSLI, R. 1986: Blue amphiboles in metamorphosed mesozoic mafic rocks from the Central Alps. Geol. Soc. Amer. Mem. 164, 238–247.

ORTNER, H. 1994: Die petrographische Entwicklung der Muttekopfgosau (Lechtaler Alpen, Tirol). Zbl. Geol. Paläont. Teil I, 11/12, 1355–1371.

PIETERS, P.E. 1978: Port Moresby-Kalo-Aroa, Papua New Guinea, 1 : 250.000 Geological Series, Explanatory Notes. Australian Gov. Publ. Serv., Canberra.

PLATT, J.P. 1986: Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. Bull. Geol. Soc. Amer. 97, 1037–1053.

POBER, E. & FAUPL, P. 1988: The chemistry of detrital chromian spinels and its implications for the geodynamic evolution of the Eastern Alps. Geol. Rdsch. 77, 641–670.

RAKUS, M., MISIK, M., MICHALIK, J., MOCK, R., DURKOVIC, T., KORAB, T., MARSCHALKO, R., MELLO, J., POLAK, M. & JABLONSKY, J. 1990: Paleogeographic development of the West Carpathians: Anisian to Oligocene. Mém. Soc. Géol. France N.S. 154 (III, pt. 1), 39–62.

RATSCHBACHER, L. 1986: Kinematics of Austro-Alpine cover nappes: changing translation path due to transpression. Tectonophysics 125, 335–356.

RICOU, L.-E. 1994: Tethys reconstructed: plates, continental fragments and their boundaries since 260 Ma from Central America to South-eastern Asia. Geodin. Acta 7, 169–218.

RING, U., RATSCHBACHER, L. & FRISCH, W. 1988: Plate-boundary kinematics in the Alps: Motion in the Arosa suture zone. Geology 16, 696–698.

ROBERTSON, A.H.F. & SEARLE, M.P. 1990: The northern Oman Tethyan continental margin: stratigraphy, structure, concepts and controversies. In: The geology and tectonics the Oman region. (Ed. by ROBERTSON, A.H.F., SEARLE, M.P. & RIES, A.C.) Geol. Soc. London Spec. Publ. 18, 3–25.

SAVOSTIN, L.A., SIBUET, J.-C., ZONESHAIN, L.P., LE PICHON, X. & ROULET, M.-J. 1986: Kinematic evolution of the Tethys belt from Atlantic ocean to the Pamir since Triassic. Tectonophysics 123, 1–35.

SCHUHMACHER, M.E., SCHÖNBORN, G., BERNOULLI, D. & LAUBSCHER, H.P. in press: Rifting and collision in the Southern Alps. In: Deep structure of the Swiss Alps: results from NFP-20. (Ed. by PFIFFNER, A. ET AL.) Birkhäuser, Basel.

SEARLE, M.P. & STEVENS, R.K. 1984: Obduction processes in ancient, modern and future ophiolites. In: Ophiolites and oceanic lithosphere. (Ed. by GASS, I.G., LIPPHARD, S.J. & SHELTON, A.W.) Geol. Soc. London, Spec. Publ. 13, 303–320.

STAMPFLI, G. 1993: Le Briançonnais, terrain exotique dans les Alpes? Eclogae geol. Helv. 86, 1–45.

STEINMANN, M. 1994: Ein Beckenmodell für das Nordpenninikum der Ostschweiz. Jb. Geol. B.-A. 137, 675–721.

THÖNI, M. 1980: Distribution of pre-Alpine and Alpine metamorphism of the southern Oetztal mass and the Scharl unit, based on K/Ar age determination. Mitt. geol. Ges. Wien 71/72, 139–165.

– 1983: The thermal climax of the early Alpine metamorphism in the Austroalpine thrust sheet. Mem. Sci. Geol. Univ. Padova 36, 211–238.

– 1986: The Rb-Sr thin slab isochron method – An unreliable geochronologic method for dating geologic events in polymetamorphic terrains? Mem. Sci. Geol. Univ. Padova 38, 283–352.

– 1988: Rb-Sr isotopic resetting in mylonites and pseudotachylites: Implications for the detachment and thrusting of the Austroalpine basement nappes in the Eastern Alps. Jb. Geol. B.-A., Wien 131, 169–201.

THÖNI, M. & JAGOUTZ, E. 1992: Some new aspects of dating eclogites in orogenic belts: Sm, Nd, Rb-Sr, and Pb-Pb isotopic results from the Austroalpine Saualpe und Koralpe typelocality (Carinthia/Styria, southeastern Austria). Geochim. Cosmochim. Acta 56, 347–368.

TILL, A.B. 1992: Detrital blueschist-facies metamorphic mineral assemblages in Early Cretaceous sediments of the foreland basin of the Brooks Range, Alaska, and implications for orogenic evolution. Tectonics 11, 1207–1223.

TOLLMANN, A. 1977: Geologie von Österreich I, Die Zentralalpen, Deuticke, Wien.

TROMMSDORFF, V. 1962: Über Lamprophyre aus den nördlichen Kalkalpen (Ehrwaldit). Tscherm. mineral. petrogr. Mitt. 8, 281–325.

TROMMSDORFF, V., DIETRICH, V., FLISCH, M., STILLE, P. & ULMER, P. 1990: Mid-Cretaceous primitive alkaline magmatism in the Northern Calcareous Alps: Significance for Austroalpine geodynamics. Geol. Rdsch. 79, 85–97.

TROMMSDORFF, V., PICCARDO, G.B. & MONTRASIO, A. 1993: From magmatism through metamorphism to sea floor emplacement of subcontinental Adria lithosphere during pre-Alpine rifting (Malenco, Italy). Schweiz. mineral. petrogr. Mitt. 73, 191–203.

TRÜMPY, R. 1992: Ostalpen und Westalpen – Verbindendes und Trennendes. Jb. Geol. B.-A., Wien 135, 875–882.

WAGREICH, M. 1988: Sedimentologie und Beckenentwicklung des tieferen Abschnittes (Santon-Untercampan) der Gosauschichten von Gosau und Russbach (Oberösterreich–Salzburg). Jb. Geol. B.-A. 131, 663–685.

– 1993: Serpentinitreiche Sandsteine als Anzeiger verschwundener Suturzonen am Beispiel der Oberkreide der Nördlichen Kalkalpen (Gosau-Gruppe, Österreich). Zbl. Geol. Paläont. Teil I, 6, 663–673.

– 1993: Subcrustal tectonic erosion in orogenic belts – A model for the Late Cretaceous subsidence of the Northern Calcareous Alps (Austria). Geology 21, 941–944.

WAGREICH, M. & FAUPL, P. 1993: Palaeogeography and geodynamic evolution of the Gosau Group in the Northern Calcareous Alps (Late Cretaceous, Eastern Alps, Austria). Palaeogeogr., Palaeoclim., Palaeoecol. 110, 235–254.

WAGREICH, M. & MARSCHALKO, R. 1995: Late Cretaceous to Early Tertiary palaeogeography of the Western Carpathians (Slovakia) and the Eastern Alps (Austria): implications from heavy mineral data. Geol. Rdsch. 84, 187–199.

WAIBEL, A.F. 1993: Nature and plate-tectonic significance of orogenic magmatism in the European Alps: a review. Schweiz. mineral. petrogr. Mitt. 73, 391–405.

WEIDICH, K.F. 1984: Über die Beziehungen des "Cenomans" zur Gosau in den Nördlichen Kalkalpen und ihre Auswirkungen auf die paläogeographischen und tektonischen Vorstellungen. Geol. Rdsch. 73, 517–566.

WEISSERT, H. & BERNOULLI, D. 1985: A transform margin in the Mesozoic Tethys: evidence from the Swiss Alps. Geol. Rdsch. 74, 665–679.

WERNICKE, B. 1985: Uniform-sense normal simple shear of the continental lithosphere. Can. J. Earth Sci. 22, 108–125.

WILDI, W. 1985: Heavy mineral distribution and dispersal pattern in penninic and ligurian flysch basins (Alps, northern Appennines). G. Geol. ser. 3/47, 77–99.

WINKLER, W. 1988: Mid- to early Late Cretaceous flysch and melange formations in the western part of the Eastern Alps. Palaeotectonic implications. Jb. Geol. B.-A., Wien 131, 341–389.

WINKLER, W. & BERNOULLI, D. 1986: Detrital high-pressure/low-temperature minerals in a late Turonian flysch sequence of the eastern Alps (western Austria): Implications for early Alpine tectonics. Geology 14, 598–601.

WINKLER, W. & SLACZKA, A. 1994: A Late Cretaceous to Paleogene geodynamic model for the Western Carpathians in Poland. Geologica carpath. 45, 71–82.

WOLETZ, G. 1963: Charakteristische Schwermineralgehalte in Kreide- und Alttertiär-Schichten der nördlichen Ostalpen. Jb. Geol. B.-A., Wien 106, 89–120.

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