

Late Jurassic to Eocene Palaeogeography and Geodynamic Evolution of the Eastern Alps

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Abstract

The Mesozoic orogeny of the Eastern Alps is controlled by subduction, collision and closure of two oceanic domains of the Western Tethyan realm: The Late Jurassic to Early Cretaceous closure of a Triassic Tethys Ocean, probably connected to the Vardar Ocean in the Hellenides, and the Mid-Cretaceous to Early Tertiary closure of the Penninic Ocean to the north of the Austroalpine unit. Based on facies analysis and provenance studies, the evolution of the major palaeogeographic domains is discussed. Ophiolitic detritus gives insights into the history of active margins and collisional events. Synorogenic sediments within the Northern Calcareous Alps from the Late Jurassic and Early Cretaceous onwards record shortening within the Austroalpine domain, due to suturing in the south and the onset of subduction of the Penninic Ocean in the north. Transtension following Mid-Cretaceous compression led to the subsidence of Late Cretaceous Gosau Basins. Tectonic erosion of the accretionary structure at the leading margin of the Austroalpine plate resulted in deformation and deepening within the Northern Calcareous Alps. Cretaceous to Early Tertiary deep-water deposition ended in a final stage of compression, a consequence of the closure of the Penninic Ocean.

Introduction

The orogenic evolution of the Eastern Alps can be divided into several stages of deformation: a Jurassic and Cretaceous (Eoalpine) stage, followed by Tertiary ones, starting in the Late Eocene (Meso- to Neoalpine orogeny). Whereas the Tertiary orogeny is constrained by a wealth of structural data (e.g. RATSCHBACHER et al., 1989, 1991, DECKER & PERSSON, 1996; FRISCH et al., 1998), the reconstruction of the Jurassic to Cretaceous geodynamics and palaeogeography is more problematic because of polyphase Tertiary deformation overprinting Mesozoic structures, the incompleteness of the sedimentary record and the less constrained palaeogeographic and palaeotectonic positions of individual tectonic domains. These led to a variety of proposed models for the evolution of the Eastern Alps during Late Jurassic to Early Tertiary times, differing especially in the inferred positions and timing of subduction zones, collisions and suturing (e.g. CHANNELL et al., 1992; FAUPL & WAGREICH, 1992a; FROITZHEIM et al., 1997; NEUBAUER, 1994; VON EYNATTEN & GAUPP, 1999; WAGREICH & FAUPL, 1994; WINKLER, 1988, 1996).

The Eastern Alps represent a highly compressed segment of the Alpine chain, located between the Rhine valley to the west and the Neogene Vienna Basin toward the east. The Eastern Alps comprise four major nappe complexes, which had been thrust onto the European plate (Fig. 1): (1) the Helvetic zone, (2) the Penninic zone, (3) the Austroalpine zone, and (4) the Southalpine zone. The Aus-

troalpine zone is subdivided into a Lower, Middle and Upper Austroalpine nappe complex. Within the Upper Austroalpine zone the Northern Calcareous Alps (NCA) represent a complicated pile of cover nappes. The classical subdivision of the NCA is distinguished from the tectonically highest (southern) to the lowest (northern) units: Juvavicum (e.g. Dachstein, Hallstatt, Schneeberg nappes), Tirolicum (e.g. Ötscher, Totengebirge, Inntal nappes), Upper Bajuvaricum (e.g. Lunz/Reichraming and Lechtal nappe), and the Lower Bajuvaricum (e.g. Frankenfels/Ternberg, Allgäu nappes).

This paper gives an overview about current concepts for the Late Jurassic to Early Tertiary orogeny within the Eastern Alps, based on the authors' investigations in syntectonic sedimentary strata, especially in the middle and eastern part of the Eastern Alps. The provenance of detrital material and mechanisms of basin formation and subsidence are discussed according to recent data and ongoing research.

Facies development

Alpine Foreland and Helvetic domain

The Helvetic realm comprises sedimentary strata deposited on the shelf and upper slope of the European continental plate (Fig. 2 – column 2). Lower Cretaceous deposits of the Helvetic realm are exposed in the western part of the Eastern Alps, forming a continuation of the broad Helvetic zone of the Central (Swiss) Alps. Above pelagic carbonates of

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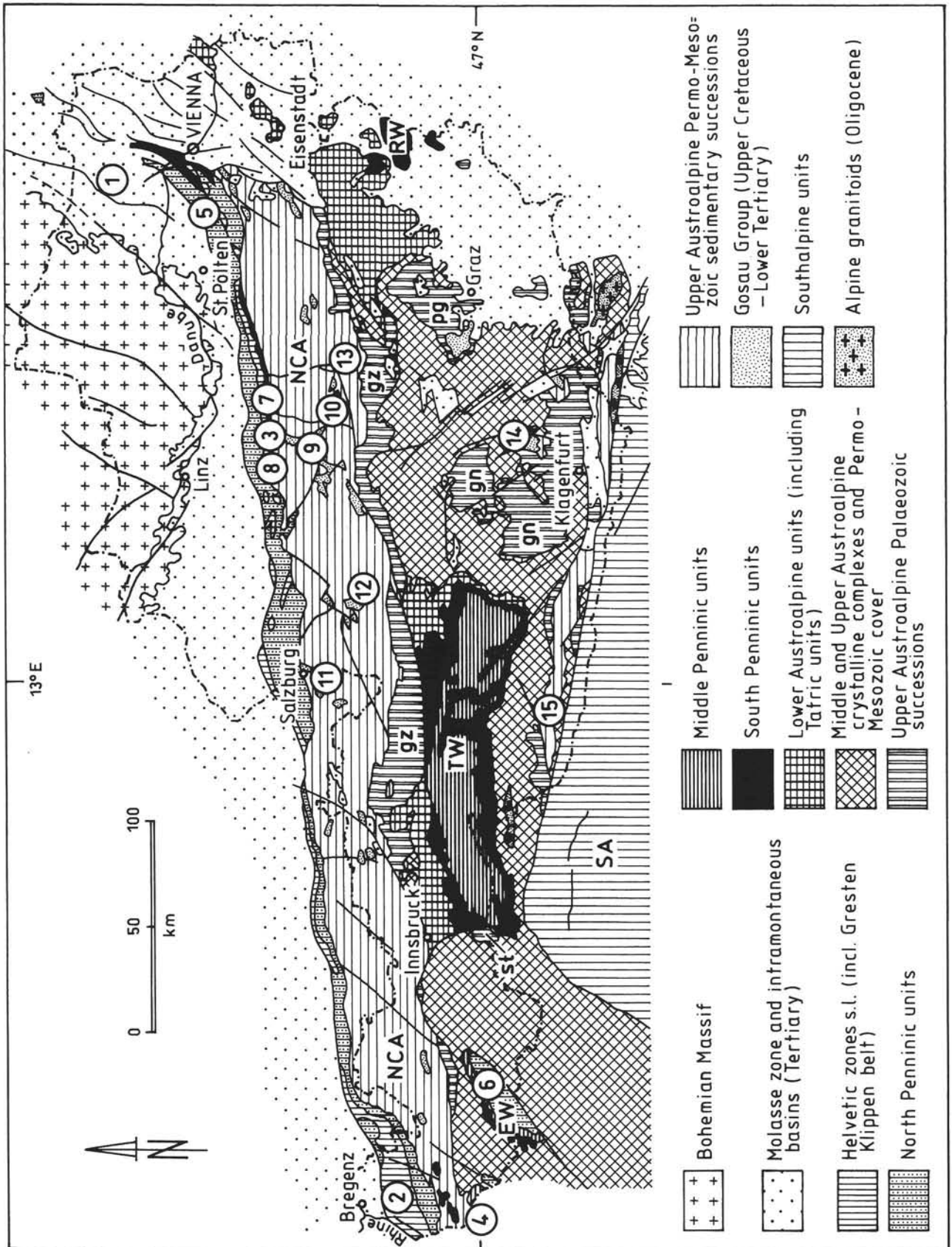


Fig. 1
Tectonic sketch map of the Eastern Alps. NCA – Northern Calcareous Alps, gz – Graywacke zone, gp – Palaeozoic of Graz, gn – Gurktal nappe complex, TW – Tauern Window, EW – Engadine Window, SA – Southern Alps. Localities 1 to 15 refer to section numbers in Fig. 2.

Late Jurassic age, rudist-bearing shallow-water carbonates of Early Cretaceous age, the Urgonian facies (e.g. Schratenkalk), developed, which interfingers toward the south with a marly facies. Accumulation on the Helvetic carbonate platform ceased several times, documented by thin phosphoric-glaucconitic horizons. After a period of reduced sedimentation, indicated by a series of condensed formations during the Mid-Cretaceous, pelagic carbonate deposits give evidence for drowning during the Cenomanian. The following pelagic Upper Cretaceous deposits comprise predominantly marls. The Helvetic shelf emerged again in the Paleocene and Early Eocene, indicated by the accumulation of nummulite and corallinacea-bearing shallow-water sediments. Overlying pelagic deposits with globigerinid foraminifera and terrigenous flysch sediments pass finally into the Molasse sediments of the Alpine foreland basin during the Late Eocene/Oligocene. The classical Helvetic facies development of the Early Cretaceous is not only confined to the Helvetic nappes s. str., but reaches also farther north into the western Alpine foreland.

The autochthonous Mesozoic successions, overlying the Bohemian Massif (basement of the European plate) and covered by sediments of the Molasse zone (Fig. 2-1), show significant differences in respect to the Helvetic deposits. There, the Upper Jurassic shallow-water carbonate platforms in the east emerged during a prominent regression at the Jurassic/Cretaceous boundary and became transgressed again during Cenomanian and Senonian times. Eastern parts of the Upper Jurassic carbonate platform (Waschberg zone) may even pass into the Berriasian (MOSHAMMER & SCHLAGINTWEIT, in press). The Cenomanian transgression of the European foreland is marked by the deposition of greensands (KOLLMANN et al., 1977; FUCHS & WESSELY, 1996), followed by marl sedimentation of Late Cretaceous age. The Palaeogene deposits exhibit terrigenous as well as carbonate shallow-water sediments. The onset of Molasse sedimentation with sands and corallinacea limestones began in the Late Eocene (e. g. WAGNER, 1996)

In contrast to the Helvetic zone s. str., the Lower Cretaceous deposits of the Ultrahelvetic zone and the Gresten Klippen belt (Fig. 1, 2 – column 3) are characterized by a deep-water carbonate facies, which is typical in the western Tethys realm. In the Gresten Klippen belt, underlying Upper Jurassic deep-water carbonate breccias were deposited on a south-facing slope (DECKER, 1987; WIDDER, 1988). The deep-water limestones are followed by a variegated marl succession ("Buntmergelserie") from the Albian on. In the Palaeogene parts of these marl successions, coarse clastic deposits with huge olistoliths of limestones, granites and related rocks, as well as turbiditic successions, are common (FAUPL, 1978a; FAUPL & SCHNABEL, 1987; FRASL, 1980; WIDDER, 1986).

Penninic domain

The Penninic zone is subdivided into the North, Middle and South Penninic units, which had already developed from the Middle Jurassic to the Cretaceous, due to extension and spreading between the European foreland/Helvetic units and the Austroalpine microplate (Fig. 3).

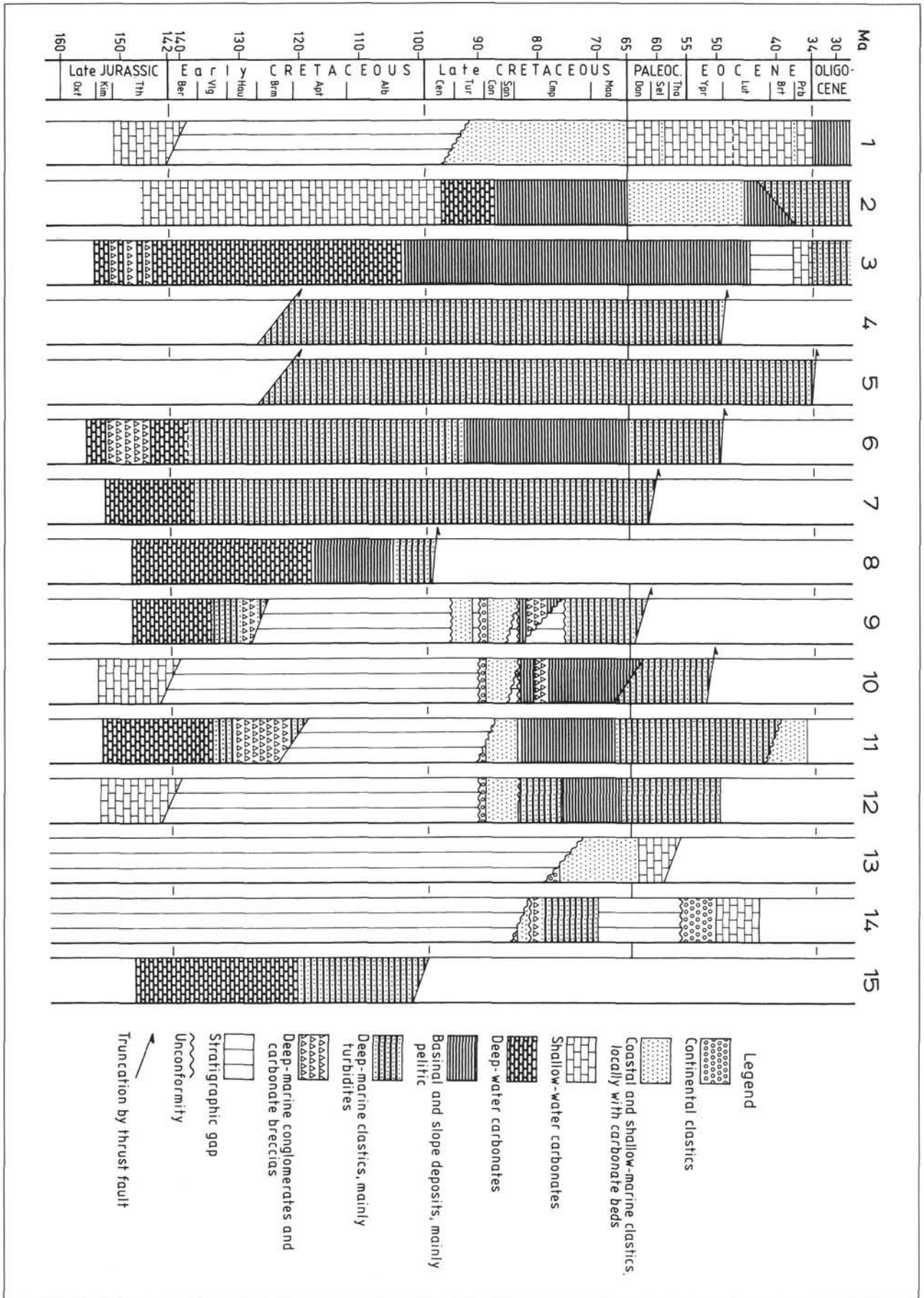
During Early Cretaceous time, from the Barremian onward, turbiditic sedimentation developed within the North Penninic domain of the Prätigau area (Eastern Switzerland)

and its eastern counterparts, in the Unterengadin Window, as well as in the Rhenodanubian Flysch zone (Fig. 1). The latter formed a separate basin, probably palaeogeographically located to the south of the Prätigau – Engadine trough. The low-grade metamorphic successions of the "Prätigau Flysch" (Fig. 2 – column 4) comprise a thick pile of terrigenous turbidites and consist mainly of carbonate-dominated turbidites in the Early Cretaceous, changing into more siliciclastic flysch deposits of the Late Cretaceous up to the Eocene. The clastic material is characterized by the predominance of stable heavy minerals.

In the *Rhenodanubian Flysch zone* (Fig. 2 – column 5), the succession also started with carbonate-dominated flysch deposits, but passed into turbidites rich in siliciclastic material in the uppermost Early Cretaceous. The Upper Cretaceous turbidite successions are subdivided by several thin-bedded variegated pelitic intervals, deposited during periods of reduced turbiditic input, probably due to relative sea-level changes. The Upper Cretaceous sandstones, especially the siliciclastic-dominated ones, contain garnet-rich heavy mineral assemblages, which is in contrast to the Prätigau Flysch. In the Campanian, basin-plain deposits rich in carbonate mud turbidites developed. The Palaeogene deposits are mainly characterized by stable heavy minerals. The change from garnet- to zircon-dominated assemblages has been observed within the up to 1500 m thick Maastrichtian – Upper Paleocene deposits. In the middle part of the Rhenodanubian Flysch zone, thin bentonite layers occur in the Paleocene/Eocene boundary interval (EGGER et al., 1997). Toward the east of the flysch zone, thick terrigenous turbidite beds of Late Paleocene – Eocene age were deposited near the present northern margin of the trough (HÖSCH, 1985; RAMMEL, 1989).

In the *Middle Penninic units*, at the western border of the Eastern Alps (Falknis/Tasna nappe, Fig. 2 – column 6), a Jurassic/Lower Cretaceous deep-water carbonate facies is common. Upper Jurassic carbonate breccias, which were formed during a rifting phase (FROITZHEIM & RUBATTO, 1998), were deposited on a north-facing slope (GRUNER, 1981). In contrast to this deep-water development, a shallow-water carbonate facies of the Late Jurassic age occurs palaeogeographically towards the south, in a separated tectonic element of the Middle Penninic domain (Sulzfluh nappe). The Lower Cretaceous succession of the Falknis-Tasna nappe shows close similarities to those of the Rhenodanubian Flysch zone (HESSE, 1973; SCHWIZER, 1984). The Upper Cretaceous sediments of these Middle Penninic units are characterized by variegated pelagic marls (Couches Rouges). The gneisses of the "Zentralgneis" unit (Venediger Nappe Complex) of the Tauern Window, whose Middle Penninic position is under debate (e.g. LAMMERER, 1986; OBERHAUSER, 1995), are covered by probably deep neritic Upper Jurassic marbles (KIESSLING, 1992; KIESSLING & ZEISS, 1992), followed by a metamorphic terrigenous succession of supposed Cretaceous age (THIELE, 1970; FRISCH, 1974). The typical Couches Rouge facies has not been observed within the Venediger Nappe Complex of the Tauern Window.

In the *South Penninic domain*, the non-metamorphic Upper Jurassic – Lower Cretaceous succession of the Ybbsitz zone (Fig. 2 – column 7), which is very similar to those of the Arosa zone in eastern Switzerland, comprises calcipionellid limestones with thin turbiditic interbeds (DECKER, 1987, 1990), overlying a radiolarite facies. The limestones pass



into carbonate-dominated flysch sediments, Albian flysch deposits rich in black shales and a siliciclastic sandy interval (HOMAYOUN & FAUPL, 1992). In the Kahlenberg nappe of the eastern Rhenodanubian Flysch zone, a probable continuation of the Ybbsitz zone (e.g. FAUPL & WAGREICH, 1992a), the turbiditic deposition ended in the lowermost Paleocene. Some of the turbidite deposits of the Ybbsitz zone commonly contain chrome spinel in the heavy mineral assemblages, a significant feature of Mid-Cretaceous flysch sediments of the South Penninic domain (e.g. LÜDIN, 1987; POBER & FAUPL, 1988). In Mid-Cretaceous turbidite deposits of the North Penninic domain, detrital chrome spinel is generally lacking.

The metamorphic South Penninic successions of the Tauern Window are subdivided into several subfacies (Brennkogel, Glockner, Fusch facies). The Brennkogel facies was deposited during the opening stage of the oceanic trough. The Glockner facies is in close relation to huge ophiolitic complexes. The so-called "Bündnerschiefer" of the Tauern Window seem to be partly a metamorphic equivalent of deep-water carbonate facies, whereas other parts were interpreted as metamorphosed turbiditic sequences. The Fusch facies probably represents Lower and Mid-Cretaceous successions, which ceased with turbiditic deposits with intercalations of coarse deep-water clastics and olistoliths (FRISCH et al., 1987).

Austroalpine domain

The Austroalpine domain is considered as a partly independent microplate/terrane at the northern margin of the Apulian plate, based on palaeomagnetic data (e.g. CHANNELL et al., 1992). The best documented sedimentary successions of the Austroalpine domain are preserved within the Northern Calcareous Alps (NCA) (Fig. 2 – columns 8 to 13). Deep-water carbonate facies, deposited below the aragonite compensation depth, already commenced in the Late Jurassic. The deep-water development passed into Lower Cretaceous deep-water sediments (Schrambach Formation), which comprises Maiolica-type limestones at their base, whereas the silt/clay content increases upsection where distinct marl interbeds occur.

Contrary to this deep-water development, an Upper Jurassic carbonate platform is preserved predominantly within the Juvavic units of the NCA, which passed locally into the Berriasian (SCHLAGINTWEIT & EBERLI, 1998). From this platform, shallow-water detritus was shed towards the north into a deep-water carbonate basin with thick allodapic layers of varying thickness (STEIGER, 1981). Resedimented clasts of Urgonian carbonates (e.g. WAGREICH & SCHLAGINTWEIT, 1990; SCHLAGINTWEIT, 1991) provide evidence that

platform carbonates were common during the Early Cretaceous, but were later completely eroded.

In the Tirolicum and Upper Bajuvaricum nappe complexes of the NCA (southern parts of the Reichraming and Lunz nappe), the deep-water limestone facies graded into a synorogenic terrigenous facies during the Valanginian to Aptian (Rossfeld Formation; Fig. 2 – column 9) (FAUPL & TOLLMANN, 1979; DECKER et al., 1987; VASICEK & FAUPL, 1996). This formation is composed of marls, turbiditic sandstones and locally of huge masses of deep-water conglomerates/breccias, as well as slump deposits sedimented on an active north-facing slope which formed within the NCA. Whereas the conglomerates consist mainly of carbonate clasts of local origin, the sandstones contain considerable amounts of siliciclastic and ophiolitic detritus. Within contemporaneous deep-water limestones to the north, distal turbidite interbeds were supplied from the same southern source terrain (VASICEK & FAUPL, in press). The oldest turbiditic interbeds with significant ophiolitic detritus were observed in Upper Berriasian deposits (VASICEK et al, in press).

During the Aptian, the synorogenic facies shifted to tectonically lower units of the NCA, such as the Frankenfels-Ternberg-Allgäu nappe system (Lower Bajuvaricum, Fig. 2 – column 8) and the so-called "Cenoman-Randschuppe". The deep-water limestones here passed into a marl succession, including black shales (Tannheim Formation; WAGREICH & SACHSENHOFER, 1999), followed by silty marls, turbiditic sandstones and several types of deep-water conglomerates, enriched with exotic clasts (Losenstein Formation; middle Albian – Lower Cenomanian). The terrigenous material of these formations, including ophiolitic detritus, gives evidence of a new source terrain located to the north of the NCA (POBER & FAUPL, 1988; VON EYNATTEN, 1996; VON EYNATTEN & GAUPP, 1999).

In the western NCA, in the Lechtal nappe, a turbiditic pelite/sandstone succession is preserved, which has a stratigraphic range from Aptian to Albian/?Cenomanian (Lech Formation; VON EYNATTEN, 1996; VON EYNATTEN & GAUPP, 1999). Palaeocurrent data give evidence of a source area located toward the south which was probably the same source as assumed for the Rossfeld Formation. A similar facies trend from deep-water limestones to distal terrigenous turbidites is preserved in the Aptian-Albian successions of the Drau Range (Fig. 2 – column 15) (Lavant Formation; FAUPL, 1976).

The onset of breccia deposition unconformably upon external parts of the Lunz-Reichraming-Lechtal nappe system (GAUPP 1980, 1982; WEIDICH 1984; FAUPL & WAGREICH, 1992b) in the Cenomanian illustrates a further step in the synsedimentary deformational history of the NCA (Branderfleck Formation; Fig. 2 – column 9). In the western NCA, basal breccias of local carbonate material pass into turbiditic successions, whereas in the middle and eastern parts, a terrigenous shelf facies predominates (FAUPL & WAGREICH, 1992b; SUMMESBERGER, 1992). In the "Cenoman-Randschuppe" of the western NCA, the deep-water sedimentation continues without interruption into the Santonian/Cenomanian (WEIDICH, 1984).

In the Late Turonian, a new sedimentary cycle started with the deposition of the Gosau Group which rests unconformably on sediments deformed during the Eoalpine orogeny. The Gosau Group of the NCA can be divided into two subgroups (FAUPL et al., 1987). The Lower Gosau Subgroup

← Fig. 2
Selected lithostratigraphic sections from tectonic units of the Eastern Alps, arranged from north to south. For locations see Fig. 1. 1 = Foreland to the east of the Bohemian Massif including Waschberg Zone; 2 = Helvetic Zone of Vorarlberg; 3 = Gresten Klippen Belt; 4 = Prätigau Unit; 5 = Rhenodanubian Flysch Zone; 6 = Tasna Unit (Unterengadine Unit); 7 = Ybbsitz Zone; 8 = Ternberg Nappe (Northern Calcareous Alps = NCA); 9 = Reichraming Nappe (NCA); 10 = Ötscher Nappe, Gams area (NCA); 11 = Tirolicum of Salzburg (NCA); 12 = Dachstein Nappe, Gosau area (NCA); 13 = Mürzalpen Nappe (NCA); 14 = Krappfeld region, Gurktal Nappe; 15 = Drau Range (Lienz Dolomites).

(Turonian – Campanian; Maastrichtian only in the east) consists of terrestrial, mainly conglomeratic deposits at the base, including bauxites, and passes into shallow-marine successions. Sandstones and sandy limestones together with rudist-bearing limestones, inner and outer shelf facies, influenced by storms and shelf/slope transitional facies are common (for details about the variety of shallow-marine facies of this subgroup see WAGREICH & FAUPL, 1994, SANDERS et al., 1997, and SANDERS, 1998). High contents of ophiolitic detritus are a locally conspicuous feature of sandstones of this subgroup (WOLETZ, 1967; WAGREICH, 1993b).

The Upper Gosau Subgroup comprises deep-water deposits, such as a marl-rich slope facies with common slump deposits (Nierental Formation; e.g. KRENMAYR, 1999), and a broad variety of deep-water clastics, deposited above or below the local calcite compensation level of the basin. Locally, these formations are associated with thick successions of deep-water breccias (Fig. 2 – column 9; Spitzengbach Formation, FAUPL, 1983). Facies distribution and palaeocurrent data of the Upper Gosau Subgroup indicate a pronounced fault-controlled relief of a generally north-facing palaeoslope. In many Gosau localities of the NCA, a conspicuous angular unconformity separates the Lower from the Upper Subgroup (RUTTNER & WOLETZ, 1956; FAUPL, 1983), and parts of the Lower Gosau Subgroup have been eroded at this unconformity. In contrast to the Lower Subgroup, the terrigenous material of the deep-water successions comprises predominantly metamorphic detritus, whereas ophiolitic fragments are mostly lacking. Shallow-water components, such as corallinacea, orbitoid foraminifera, bryozoa etc., point to active shelf carbonate production in the south of the NCA. In the Paleocene and Eocene, the deep-water deposits already covered most of the NCA. Remnants of Palaeogene shallow-water carbonates have been detected towards the south (Fig. 2 – column 13, Kambübel Limestone; TRAGELEHN, 1996).

Gosau deposits rest also unconformably on the Upper Austroalpine units of the Palaeozoic of Graz (Kainach Gosau) and the Gurktal Nappe (Fig. 2 – column 14) (Krappfeld Gosau, Gosau of St. Paul/Lavanttal), which are summarized under the term "Centralalpine Gosau". Sedimentation commenced not before the Late Santonian, comprising a terrestrial to shallow-marine lower succession and an upper succession with deep-water sediments. In the Krappfeld Gosau, huge masses of sediments of the lower part, such as rudist limestones, were redeposited into the deep-water facies (NEUMANN, 1989). Clasts of the Austroalpine crystalline basement and ophiolitic detritus are absent, but fragments of Southalpine provenance have been reported from the Kainach Gosau (GOLLNER et al., 1987). In the Krappfeld area, the sedimentation of deep-water deposits ceased in the Late Campanian. During the Paleocene – Eocene, a new sedimentary cycle (Guttaring Group) started unconformably above the Gosau sediments, comprising a succession of shallow-marine terrigenous facies with coal-bearing beds passing upwards into shallow-marine limestones with nummulite beds (WILKENS, 1989). Contrary to the underlying Gosau sediments, the sandstones contain ophiolitic material.

A very small occurrence of nummulite-bearing limestones of Late Eocene age resting on the Lower Austroalpine crystalline basement complex in Lower Austria, and Eocene

marine limestone pebbles in Miocene conglomerates provide evidence of a more widespread post-Gosau sedimentary cover of the Eastern Alps, which coincides with the beginning of the Molasse sedimentation. The Upper Eocene to Oligocene deposits of the Inn Valley ("Unterinntal-Tertiär") also indicate a transgression from the Molasse basin into the NCA.

Jurassic geodynamic evolution

The geodynamic evolution of the Eastern Alps during the Jurassic was controlled by two major plate tectonic events (Fig. 3): (1) The opening of the Penninic Ocean between the European and the Austroalpine domain and (2) the closure of the Permo-Triassic Tethys Gulf within the Austroalpine-Southalpine domain.

Opening of the Penninic ocean

The original position of the Penninic Ocean within the Eastern Alps as a continuation of the Ligurian-Piemontais Ocean of the western Alps (= Alpine Tethys, STAMPFLI et al., 1998) can be reconstructed based on ophiolite complexes and their sedimentary cover. The present spur of the Penninic Ocean is marked mainly by harzburgitic ophiolite complexes (HÖCK & KOLLER, 1989). At the front of the NCA in Lower Austria, a highly dismembered ophiolite succession is preserved in the Ybbsitz zone (Fig. 1, 2 – column 7), which also represents a part of the Penninic Ocean (DEKKER, 1990; SCHNABEL, 1992). The generally high amount of serpentinites as constituents of the Penninic ophiolite complexes, accompanied, to a variable extent, by ophiolitic rocks, gives evidence of a formation in a low-spreading ridge regime comparable to the Atlantic ocean (e.g. KOLLER & HÖCK, 1990; FRISCH et al., 1994). The age of the oceanic crust, represented by the ophiolite complex, is constrained by Mn-Fe-bearing ore deposits, cherts and radiolarites of late Callovian to Oxfordian age (OZVOLDOVA & FAUPL, 1993).

The external (northern) margin of the Austroalpine domain suffered a transtensional deformation as a consequence of rifting and oblique spreading of the Penninic Ocean from Jurassic time on. Within this sinistral shear regime, Jurassic marine breccia successions developed along this Austroalpine margin (Lower Austroalpine units, FINGER, 1978; HÄUSLER, 1988). Ultrabasic detritus was reported from sandstones of Middle Jurassic age (Tarntal Mountains, HÄUSLER, 1988), probably due to transpression during rifting.

The opening of the Penninic Ocean also influenced the palaeogeographic domains towards the north of it. The European margin became unstable, which resulted in the separation of continental fragments known as Briançonnais or Middle Penninic units in the Western and Central Alps (e.g. FRISCH, 1979; STAMPFLI, 1993). A similar palaeogeographic position is assumed for the "Zentralgneiss nappe complex" of the Tauern Window. Consequently, during Cretaceous time, a North Penninic position of the Rhenodanubian Flysch zone is favoured.

Mainly Lower Jurassic breccia-bearing successions in the Tauern Window (Brennkogel Formation) are interpreted as a sedimentary facies derived from the northern margin of the South Penninic Ocean. Further Jurassic breccias related to

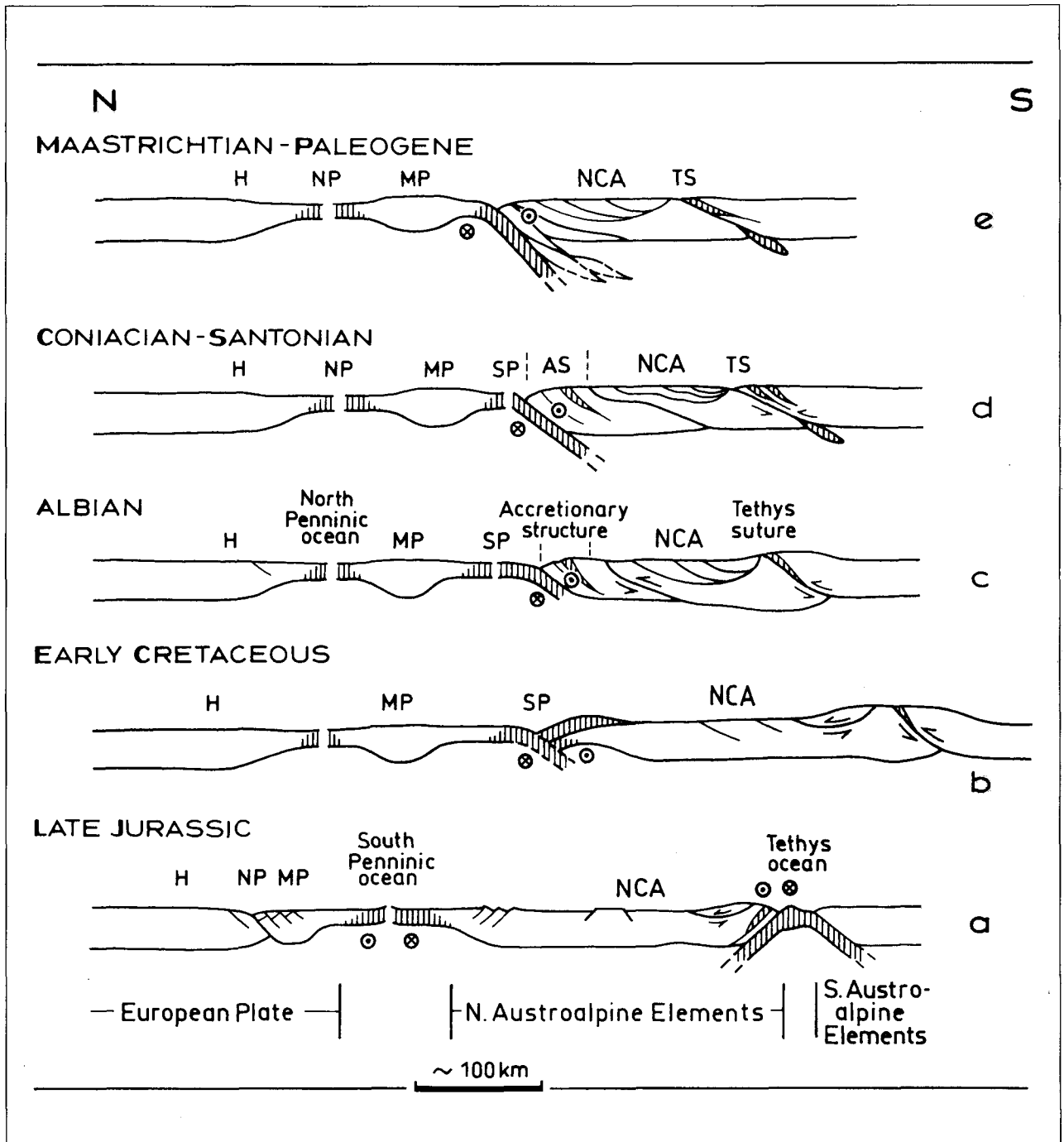


Fig. 3

Plate tectonic model for the evolution of the Eastern Alps during the Late Jurassic to Paleogene. Abbreviations: H = Helvetic/Ultrahelvetic units, NP = North Penninic Units, MP = Middle Penninic Units ("Zentralgneis"), SP = South Penninic Units, NCA = Northern Calcareous Alps, N. Austroalpine Elements = Northern Austroalpine Elements such as the Northern Calcareous Alps, S. Austroalpine Elements = Southern Austroalpine Elements such as the Drau Range.

the rifting process occur along the Helvetic/Penninic margin (Konradshelm Formation; Gresten Klippen zone) and within the Penninic realm (Falknis Breccia). The occurrence of these breccias could be an indication of the development of a rift shoulder to the north of the Penninic Ocean (comp. STAMPFLI et al., 1998). The deep-water carbonate sedimentation was in contrast with the Upper Jurassic epicontinental shelf sediments of the Alpine foreland (WAGNER, 1996).

Closure of the Tethys

The second major event during the Late Jurassic was the closure of the Permo/Triassic Tethys Gulf, resulting in the formation of a suture zone situated palaeogeographically towards the south of the NCA. The Jurassic tectonics and the position of the Jurassic collision zone within the tectonic framework of the Eastern Alps is under debate. Various models exist, which are highly influenced by the way of

palaeogeographic restoration of the Triassic facies zones within the western Tethys and by the assumed positions of the Austroalpine basement complexes (see NEUBAUER, 1994; HAAS et al., 1995; GAWLICK et al., 1999). The reconstruction of the suture zone is based on resedimented Hallstatt-Meliata rock fragments and on Cretaceous ophiolitic detritus (e.g. DECKER et al., 1987; POBER & FAUPL, 1988; WAGREICH, 1993b), as well as on comparison with the Dinarides and Hellenides, where the closing of the Vardar and Pindos Oceans as parts of the Tethys Ocean also started in the Jurassic (e.g. ROBERTSON et al., 1991). The closure of the Tethys has to be seen in connection with global plate movements, such as the opening of the North Atlantic and the Penninic Ocean.

There is broad agreement that the palaeogeographical position of the suture zone is related to the concept of the position of the Hallstatt and Meliata zone. Both the Hallstatt zone of the NCA and the Meliata zone in the Western Carpathians originally represented a transitional part of the huge Triassic carbonate platform to the Tethys Ocean. The Meliata zone is a tectonic element of the Inner Western Carpathians, containing olistoliths of Triassic radiolarites embedded within Jurassic flysch sediments (KOZUR & MOCK, 1985). Triassic ophiolites are preserved in an evaporitic melange (comparable to the "Haselgebirge" of the NCA; RÉTI, 1985). Tectonic remnants of the Meliata zone have also been found in the eastern part of the NCA (Florianokegel, MANDL & ONDREJICKOVA, 1991; KOZUR & MOSTLER, 1992). Clasts of Triassic radiolarites have been reported from Jurassic deep-water deposits (Strubberg Formation) in the middle part of the NCA (GAWLICK, 1993). The Hallstatt zone is characterized by Triassic pelagic limestones which contrasts to the shallow-water developments further to the north (Hauptdolomit, Dachsteinkalk facies). A facies restoration of the nappe pile of the NCA provides good evidence of a transitional position of the Hallstatt facies belt between the Triassic carbonate platform with the Dachstein facies towards the north and the Tethys Ocean towards the south (HAAS et al., 1995; MANDL, 1999). Based on this facies concept, the position of the suture zone is assumed to have originally been towards the south of the NCA, whereas the recent tectonic position of the Hallstatt zone (Lower Juvavic nappes) between the nappe system of the Tirolicum and the Upper Juvavic nappes (e.g. Dachstein nappe) would suggest a position of the oceanic suture within the NCA (Meliata – Hallstatt Ocean; KOZUR, 1991; NEUBAUER, 1994; CHANNELL & KOZUR, 1997). Considering the Triassic facies distribution, the authors follow the palaeogeographic restoration of LEIN (1987) and HAAS et al. (1995), placing the oceanic domain toward the south of the NCA.

Collision probably took place in a left-lateral transpressional regime with deformation, tectonic stacking and HP/LT-metamorphism of parts of the Meliata and Hallstatt zone starting in Late Callovian times (GAWLICK et al., 1999; comp. Tab. 1). From uplifted parts of the suture zone, tectonic slices of the Hallstatt facies slid gravitationally towards the north into a deep-water radiolarite basin in Oxfordian times. Redeposition of blocks of the Hallstatt facies belt continued up to the Early Cretaceous (e.g. PLÖCHINGER, 1976; TOLLMANN, 1987). As a consequence of the formation of the Tethys suture zone, compressional tectonics within the NCA started in the Jurassic, predominantly confined to the upper tectonic units (Juvavicum) representing the palaeogeog-

raphically southern part of the NCA. In the lower tectonic units (Tirolicum and Bajuvaricum) Late Jurassic subsidence was mainly controlled by E-W oriented normal faults (CHANNELL et al., 1992) offering evidence of continuing extension. At the end of the Jurassic, deep-water carbonate accumulation took place on these lower tectonic units, whereas on the higher tectonic units, a carbonate platform was established.

PLÖCHINGER (1976) and CHANNELL et al. (1992) suggested halokinetic and gravity sliding processes as the main processes during the Jurassic. However, radiometric dating of metamorphism of the Upper Permian evaporitic melange from the base of the NCA together with HP/LT-metamorphic blocks give evidence of a Late Jurassic thrusting and subduction event (SPÖTL et al., 1996; SPÖTL & HASENHÜTTL, 1998; GAWLICK et al., 1999). In the model of CHANNELL et al. (1992), these tectonic processes started within a dextral transpressional regime between the NCA and the Southern Alps in the Early Cretaceous. According to our concept, a sinistral transpressional regime between the NCA and the southern units is postulated, because the eastward tectonic escape of the Drau Range and related palaeogeographic elements, such as the Transdanubian Range, should have started with the formation of the Tethys suture zone.

Early Cretaceous synorogenic sedimentation and the Eoalpine orogeny

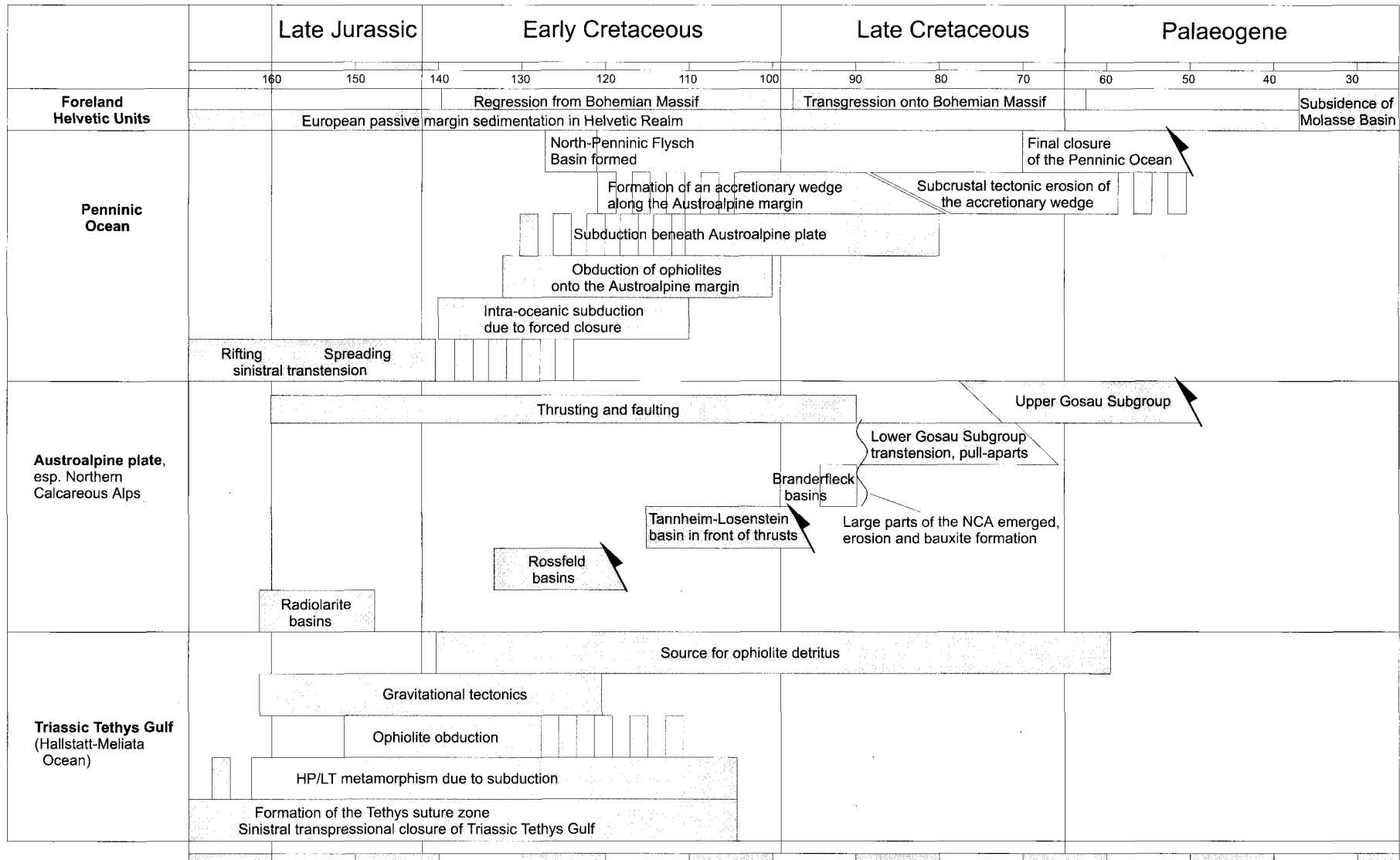
The Eoalpine orogenic events were confined to the Austroalpine and the adjacent South Penninic domains. Respectively, two plate tectonic events influenced the Early to Mid-Cretaceous evolution of this realm (Fig. 3): (1) the persistent closure of the Tethys Ocean and (2) the beginning of the subduction of the Penninic Ocean.

Towards the south of the NCA, in present geographic terms, the Tethys suture zone with a transpressional regime had been active since the Jurassic. During the Early Cretaceous, the belt of compressional deformation shifted from the southern, higher tectonic units of the NCA stepwise toward the north, into the Tirolicum and Bajuvaricum, indicated by the onset of synorogenic sedimentation in these tectonic units (Tab. 1). In the Tirolicum and upper units of the Bajuvaricum, deposition of the deep-water clastics of the Rossfeld Formation commenced in the Upper Valanginian.

Information about the configuration and composition of the Tethys suture zone is limited. From the Berriasian on, the massive input of chrome spinel of harzburgitic derivation was observed (FAUPL & POBER, 1991; VON EYNATTEN, 1996; VASICEK et al., in press) which demonstrates that ophiolites of a suggested arc-related origin had been obducted immediately before. The chemical composition of the detrital chrome spinels with an assumed provenance from the Tethys suture zone is very uniform (ARGYELAN, 1996; FAUPL et al., 1997). An arc-related signature was also reported from sandstone geochemistry of the Rossfeld Formation (SCHWEIGL & NEUBAUER, 1997). Detrital chrome spinel from Mid-Cretaceous and Upper Cretaceous sandstones derived from the Tethys suture zone show a broader geochemical range than those from the Lower Cretaceous, which can be explained by an additional contribution of Iherzolitic complexes of MORB-affinity in the suture zone (POBER &

Table 1

Major events during the evolution of the Tethys Ocean, the Austroalpine sedimentary cover, and the Penninic Ocean during the Late Jurassic to Early Tertiary. Arrows indicate overthrusting.



FAUPL, 1988). This geochemical trend can be interpreted as the result of further obduction events during the Cretaceous evolution of the Tethys suture zone.

Further proof of active subduction within the Tethys suture zone during the Cretaceous comes from the occurrence of high-pressure rock complexes, mainly eclogitic assemblages, with Cretaceous cooling ages in the Koralpe (THÖNI & JAGOUTZ, 1993). CHANNELL et al., (1992) also interpreted the high-pressure rocks of the Kreuzeck and Texel Mountains, as well as those of the Sesia-Lanzo zone, as a continuation of the Tethys suture zone towards the west.

The onset of syntectonic sedimentation in the NCA during the Early Cretaceous has been interpreted as the sedimentary signal of the tectonic decoupling of the NCA from their crystalline basement. Early Cretaceous radiometric data from the base of the NCA (KRALIK et al., 1987) are believed to correlate with this tectonic event. The Mid-Cretaceous synorogenic deposits of the NCA point to a newly formed source terrain to the north, as indicated by palaeocurrent data (GAUPP, 1982). This northern source terrain is considered to be a result of subduction processes of the Penninic Ocean underneath the northern Austroalpine margin which formed an accretionary complex during the Mid-Cretaceous (Fig. 4). The source area is composed of crystalline basement rocks and a sedimentary cover as well as ophiolite complexes (e.g. GAUPP, 1982). On this elevated ridge, Urgonian shallow-water limestones developed, which can be concluded from pebbles in synorogenic deep-water sediments. The synorogenic sedimentation ended by overthrusting and a new sedimentary cycle developed on the hangingwall of the thrust during the Cenomanian (Branderfleck Formation).

The significance of this accretionary structure as a source terrain at the northern margin of the Austroalpine microplate can also be documented by the abundance of ophiolitic detritus in the Mid-Cretaceous deposits of the South Penninic units, e.g. in the Arosa zone (LÜDIN, 1987) and related elements such as the Ybbsitz zone. The analytical data of the detrital chrome spinels from the Mid-Cretaceous sediments exhibit a specific geochemical trend, which is clearly distinguishable from detritus of the Tethys suture zone (POBER & FAUPL, 1988, VON EYNATTEN, 1996).

In the synorogenic Mid-Cretaceous sediments, detrital minerals of high-pressure origin, such as blue alkali amphiboles, lawsonite, and phengite, have been detected (e.g. WINKLER & BERNOULLI, 1986). It was generally believed that these minerals are documents of an Early Cretaceous subduction metamorphism and the following rapid exhumation of high-pressure rocks. However, Ar/Ar ages of detrital phengites indicate a Variscan high-pressure metamorphism. Because of the positive correlation between the abundance of detrital phengite and of alkali amphiboles, VON EYNATTEN & GAUPP (1999) consequently interpreted both detrital high-pressure minerals as erosional products of a Variscan basement slice.

The idea of Early Cretaceous subduction of the Penninic Ocean underneath the deformed Austroalpine margin is predominantly deduced from sedimentary data (Fig. 4, Tab. 1), but is not directly supported by radiometric data from the Penninic zone. The wide range of the Cretaceous to Eocene radiometric ages from subduction-related HP/LT-metamorphic rocks in the Penninic and Austroalpine domain is now under debate (THÖNI, 1999). Structural analysis

in the Penninic and the Austroalpine units indicate a tectonic transport toward the west or northwest (e.g. RATSCHBACHER, 1987; RING et al., 1988; DECKER et al., 1993). Therefore, an oblique dextral subduction regime for the segment of the Eastern Alps is assumed.

A classic problem for geodynamic models displays the lack of a Cretaceous magmatic arc in connection with the subduction of the Penninic Ocean. Since we interpret the onset of subduction as having been forced by plate movements (FRISCH, 1979), a first subduction zone probably developed at the mid-ocean ridge as an intraoceanic subduction zone (Fig. 3b). Huge parts of the oceanic crust were obducted onto the Austroalpine margin (WINKLER, 1996) and could not contribute to the formation of a magmatic arc. After the obduction, the subduction zone shifted to the Austroalpine plate margin in a dextral transpressional regime. The occurrence of ophiolitic detritus in Aptian synorogenic sediments can also be explained by such a model.

The geochemistry of 100 Ma old basanitic dykes (Ehrwaldite), which occur in the southern parts of the Lechtal nappe of the western NCA, gives evidence that during the Mid-Cretaceous a subcontinental mantle was still present below this part of the NCA and that a Penninic subduction zone had no influence on the melt generation (TROMMSDORFF et al., 1990). From this observation it can be deduced that the total decoupling of the nappes of the Bajuvaricum from its basement had not taken place until Late Albian time. However, sedimentological data imply that the frontal elements of the NCA had already suffered a thrust deformation which started in the Aptian (GAUPP, 1982).

The Eoalpine orogeny, which affected only the Austroalpine domain and southernmost parts of the Penninic realm, seems to be mainly a consequence of the collisional events at the Tethys suture zone (CHANNELL et al., 1992) and not so much of the subduction of the Penninic ocean underneath the northern Austroalpine margin. Up to the Turonian, in the Austroalpine domain, the major tectonic nappe structures had already developed, such as the Lower, Middle and Upper Austroalpine tectonic nappe complexes. The NCA were totally decoupled from their crystalline basement and the nappe structures, as well as the large fold tracks, were formed. The Austroalpine crystalline basement complexes, as well as parts of the Palaeozoic to Mesozoic cover nappes, suffered a very-low grade up to amphibolite and eclogite facies metamorphism (FREY et al., 1999). Based upon a restoration of late Tertiary fault tectonics (FRISCH et al. 1998), it is suggested that the Cretaceous "Eastern Alps" had little more than half the length of the present-day mountain chain. As a result of Eoalpine orogeny, large parts of the highly deformed Austroalpine domain had been elevated above sea level and a land surface was formed under a subtropical climate.

The opening of the North Penninic trough and the onset of turbiditic sedimentation appears to correlate with the beginning of subduction in the South Penninic ocean (Tab. 1) (FAUPL, 1978b; FRISCH, 1979). In the Helvetic domain, the formation of a separate Ultrahelvetic zone as a mobile margin of the European plate can also be seen as a result of extension and subsidence within the North Penninic trough. The Helvetic shelf was largely controlled by eustatic sea-level changes (e.g. FÖLLMI et al., 1994) and shows no influence from orogenic events within the orogenic wedge of the Eastern Alps.

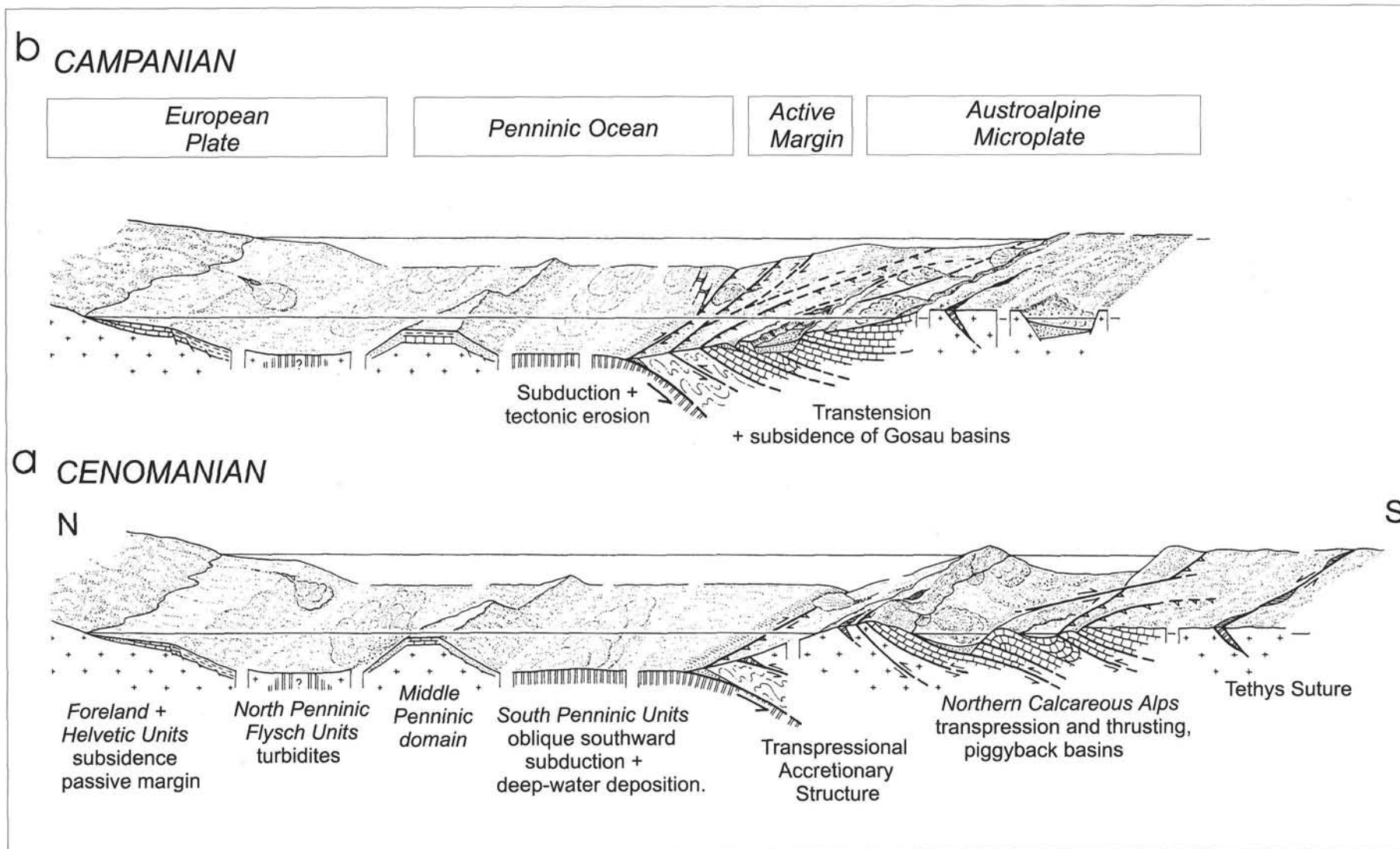


Fig. 4 Palaeogeographic transect and sedimentary basins of the Eastern Alps during the Late Albian and Campanian.

The Late Cretaceous evolution of the Austroalpine-Penninic active margin

As a consequence of the Eoalpine orogeny, most of the deformed Austroalpine domain had been uplifted above sea level in the Turonian. In front of the Austroalpine microplate, an accretionary wedge existed, which had been formed by subduction of the Penninic ocean under a dextral transpressional regime since the Mid-Cretaceous. This wedge comprised tectonic slices of Austroalpine units, including high-pressure series and obducted ophiolitic complexes. The NCA, which had been already sheared off from their crystalline basement, were situated immediately behind the tectonically active continental margin resting on a tectonically thickened crust. However, contrary to the compressional tectonics in the NCA during the Mid-Cretaceous, transtensional tectonics predominated, from the Late Turonian onwards, resulting in basin subsidence. The sedimentary succession of the Lower Gosau Group unconformably overlies an erosional surface and is characterized by terrestrial and shallow-marine environments. Rapid lateral changes in depositional thickness and facies development suggest that not only a pre-existing relief, but also synsedimentary fault tectonics were the controlling factors (WAGREICH, 1995; SANDERS et al., 1997). Pull-apart tectonics along dextral, NW-SE trending strike-slip faults played an important role during initial basin formation. Tectonic subsidence rates are high, up to 400 m per Ma (WAGREICH, 1995). Beside major amounts of local clastic material, exotic material derived from two tectonically active source terrains, the accretionary wedge toward the north of the Austroalpine plate, and from parts of the Tethys Suture zone toward the south. Both source terrains supplied ophiolitic detritus, which resulted locally in the deposition of serpentinitic sandstones (WAGREICH, 1993b).

A sudden change from shallow-water to deep-water deposits commenced in the Santonian/Campanian in the present northwestern part of the NCA and migrated with time towards the southeast. The easternmost parts of the NCA were involved in Maastrichtian and Paleocene times. In several Gosau localities, such as Weißwasser and Gießhübel, the deep-water sediments unconformably rest on deformed deposits of the Lower Gosau Subgroup, and considerable parts of the underlying strata had been eroded. After this phase, rapid subsidence resulted in a pronounced north-facing slope with marl-rich sedimentation of the Upper Gosau Subgroup, leading regionally to water depths below the local calcite compensation level (Fig. 4). The high amount of terrigenous components in the turbiditic deposits were derived from a source terrain to the south of the NCA, comprising low- to high-grade metamorphic basement complexes of Austroalpine origin. Ophiolitic complexes of the former Tethys suture zone played only a very subordinate role (e.g. FAUPL, 1983). Mica schist clasts with Permian metamorphism have been reported from Maastrichtian turbiditic sandstones (FRANK et al., 1998), which demonstrate that higher structural units of the southern Austroalpine basement, not affected by Eoalpine metamorphism, had been a part of this source area. On the other hand, the occurrence of detrital white mica with Cretaceous cooling ages was also reported from the Upper Gosau Subgroup (POBER, 1984). These ages in the range of 90–80 Ma are widely distributed within deeper parts of the Austroalpine basement (FRANK et al., 1987).

The strong subsidence of the NCA and the loss of the northern source terrain, which is related to the change from the Lower to the Upper Gosau Subgroup, can be explained by subcrustal tectonic erosion, eliminating parts of the accretionary structure situated along the margin of the Austroalpine plate (Fig. 3e). The subcrustal tectonic erosion was triggered by collisional events of oceanic positive sea-floor features or thinned continental crust remnants of the subducting Penninic realm. The subsidence curves of the Upper Gosau Subgroup are in good agreement with recent observations along active plate margins (WAGREICH, 1993a, 1995).

An alternative model is suggested by FROITZHEIM et al. (1997), in which the Late Cretaceous extension within the Austroalpine realm is explained by a subduction rollback of the Penninic subduction zone to the west within the Piemont-Liguria ocean. This model is not favoured by the present authors, because it neither explains the existence of an accretionary source terrain along the entire northern margin of the Austroalpine domain, nor the stepwise elimination of this structure from the Santonian/Campanian onward.

Basin formation within a sinistral wrench corridor is considered for the Centralalpine Gosau deposits by NEUBAUER et al. (1995). These deposits, unconformably resting on the Upper Austroalpine nappes of the Palaeozoic of Graz and the Gurktal nappe complex, contain no coarse terrigenous clasts of the Austroalpine crystalline basement, but in case of the Kainach Gosau, bear clasts of the Southalpine realm (GOLLNER et al., 1987). In the Kainach Gosau basin, main subsidence occurred during late Santonian to early Campanian. Heavy minerals of a mesozonal metamorphic terrain, described from a lacustrine facies of this basin (RUSSEGGER et al., 1998), suggest that the basin formation has been structurally related to the evolution of the metamorphic Gleinalm dome (NEUBAUER et al., 1995). A Campanian subsidence pulse is also recorded in the deposits of the Krappfeld Gosau, and a similar subsidence history was reconstructed for the Upper Cretaceous sediments of the Transdanubian Central Range in Hungary (WAGREICH & SIEGL-FARKAS, 1999).

In the Penninic realm, flysch sedimentation in the South Penninic trench lasted up to the Early Paleocene (e.g. in the Kahlenberg Nappe). The subduction of the North Penninic flysch trough took place in the Eocene. In the Middle Penninic units, chaotic deposits indicative of the subduction stage were sedimented above the pelagic facies. In the foreland, the Cenomanian transgression around the Bohemian Massif (FUCHS & WESSELY, 1996) may correspond to basin subsidence in the Bohemian Cretaceous Basin.

During the Paleocene and Eocene, the deposition of turbiditic and chaotic sediments in the Ultrahelvetetic realm s. l. points out that the collisional front had already approached the southern parts of the European foreland, creating an initial foreland bulge, which acted as a source area.

Conclusions

The Late Jurassic to Early Tertiary orogenic evolution of the Eastern Alps is characterized by several intervals of deformation and synorogenic sedimentation. An overview of the major steps in the evolution is given in Table 1.

Alpine orogeny commenced with the closure of the Triassic Tethys Gulf within the Austroalpine domain during the Jurassic (Fig. 3a). Contemporaneously, the Penninic Ocean developed by oblique rifting and spreading between the European domain and the Austroalpine microplate. Jurassic subduction processes in the Tethys Ocean, HP/LT-subduction-related metamorphism and tectonic stacking formed an elevated suture zone towards the south of the NCA, in present geographic coordinates, from which gravitational nappes and olistoliths glided into a radiolarite basin situated on the northern part of the NCA from the Late Jurassic on. As a consequence of the obduction of ophiolite bodies onto this suture zone, ophiolitic detritus had been shed into the NCA from Early Cretaceous times on (Fig. 3b). Then the compressional front progressively reached more northern (external) parts of the Austroalpine domain during the Valanginian to Turonian, accompanied by a shift in synorogenic deep-water clastic sedimentation. As a consequence of these compressional phases, governed mainly by compression within the Tethys suture zone, the Penninic Ocean changed from a transtensional into a transpressional regime (Fig. 3b). During the Early Cretaceous, parts of the Penninic Ocean were obducted onto the Austroalpine margin and the subduction zone shifted southward from internal parts of the ocean towards the northern Austroalpine margin, where a transpressional accretionary structure developed, which acted as a source terrain for synorogenic sediments (Fig. 3b, c, 4a). During the climax of Eoalpine orogeny, in the Albian – Turonian, the sedimentary cover of the NCA were sheared off from their basement and were stacked into a complex nappe pile. The basement nappes also suffered intensive deformation and metamorphism.

By the end of the Eoalpine orogeny, large parts of the deformed Austroalpine units had been elevated above sea level. Transtension behind the accretionary structure, in front of the active Austroalpine margin, resulted in the formation of pull-apart basins of the Gosau Group, comprising terrestrial and shallow water deposits (Fig. 3d, 4b). The subduction of the Penninic Ocean underneath the Austroalpine plate was still active until the Palaeogene (Fig. 3e). In the Penninic domain synorogenic flysch deposition was wide-spread. As a consequence of subcrustal tectonic erosion, the accretionary structure along the leading edge of the Austroalpine plate was eliminated and rapid subsidence occurred during the Late Cretaceous, which resulted in the deposition of terrigenous deep-water sediments of the Upper Gosau Subgroup (Fig. 3e, 4b). During the Eocene, flysch deposition characterized most of the Alpine domains of the Eastern Alps as an indication of the Mesosalpine shortening phase.

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