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Mesozoic paleogeography and the timing of eclogite-facies metamorphism in the Alps: A working hypothesis

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Key words: Alps, paleogeography, eclogites, subduction, Piemont-Liguria ocean, Valais ocean, Meliata-Hallstatt ocean

ABSTRACT

The paleogeographic evolution of the Alps during the Mesozoic was controlled by three basins partly underlain by oceanic lithosphere. These basins are of different age, becoming younger from SE to NW: the Meliata-Hallstatt basin (opened in the Middle Triassic, closed in the Late Jurassic), the Piemont-Liguria basin (opened in the Middle Jurassic, closed in the Paleocene to Early Eocene), and the Valais basin (opened in the Late Jurassic to Early Cretaceous, closed in the Eocene). Alpine orogeny involved subduction, collision, and collapse processes that occurred at different times in the different paleogeographic realms. Two orogenic cycles, a Cretaceous and a Tertiary one, can be distinguished. Cretaceous orogeny encompasses collision between the Austroalpine continental crust and a continental fragment to the east, after closing of the Meliata-Hallstatt basin. In this collision, the Austroalpine units represented the lower plate. In the Late Cretaceous, Piemont-Ligurian oceanic lithosphere together with part of the Margna-Sesia continental fragment was subducted under the Apulian (Austroalpine – South Alpine) margin. Eclogite metamorphism in the Austroalpine and in the Sesia zone is considered to be Cretaceous in age. The direction of shortening during the Cretaceous orogeny was east-west. In contrast, shortening in the Tertiary orogeny was north-south-directed in the Central and Eastern Alps. It amounted to about 500 km and led to the closure of the Piemont-Ligurian basin, the progressive incorporation of Briançonnais units in the orogenic wedge, the closure of the Valais basin, and the incorporation of European continental margin units. Substantial volumes of oceanic and continental crust were subducted during the Tertiary orogeny, and partly exhumed again. This second eclogitic stage is latest Cretaceous to Eocene in age and affected Piemont-Liguria ophiolites, the "internal massifs", Valais ophiolites, and distal European margin units such as the Adula nappe.

ZUSAMMENFASSUNG

Die mesozoische Paläogeographie der Alpen wurde durch die Öffnung und Schliessung von drei Becken mit teilweise ozeanischem Untergrund geprägt. Das Alter dieser Becken nimmt von SE nach NW ab: Das Meliata-Hallstatt-Becken öffnete sich in der Mitteltrias und wurde im späten Jura geschlossen; das piemont-ligurische Becken existierte als ozeanischer Bereich zwischen dem mittleren Jura und dem Paläozän bis frühen Eozän; das Valais-Becken schliesslich wurde etwa an der Jura-Kreide-Grenze geöffnet und im Eozän geschlossen. Die alpine Orogenese umfasst Subduktions-, Kollisions- und Kollaps-Prozesse, welche in den verschiedenen paläogeographischen Bereichen zu verschiedenen Zeiten abliefen. Zwei orogene Zyklen, von kretazischem und tertiärem Alter, lassen sich unterscheiden. Die kretazische Orogenese umfasst die Kollision zwischen der ostalpinen kontinentalen Kruste und einem östlich davon gelegenen kontinentalen Fragment, im Zusammenhang mit der Schliessung des Meliata-Hallstatt-Beckens. Die ostalpinen Einheiten stellten bei dieser Kollision die untere Platte dar. In der späten Kreidezeit wurde piemont-ligurische ozeanische Lithosphäre zusammen mit Teilen des Margna-Sesia-Kontinentalfragments unter den apulischen (ostalpin-südalpinen) Kontinentalrand

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subduziert. Diese Prozesse führten zur kreidezeitlichen eklogitfaziellen Metamorphose im Ostalpin und in der Sesia-Zone. Die Verkürzungsrichtung während der Kreide-Orogenese war Ost-West. Im Gegensatz dazu war die tertiäre Orogenese in den Zentral- und Ostalpen von Nord-Süd-Konvergenz geprägt. Diese Konvergenz belief sich auf etwa 500 km und führte nacheinander zur Schliessung des piemont-ligurischen Beckens, zur progressiven Akkretion der Briançonnais-Einheiten an den Orogenkeil, zur Schliessung des Valais-Beckens und zur Akkretion von Einheiten des europäischen Kontinentalrandes. Beträchtliche Volumina von ozeanischer und kontinentaler Kruste wurden während der tertiären Orogenese subduziert und teilweise wieder exhumiert. Dieses zweite eklogitische Stadium dauerte von der spätesten Kreide bis ins Eozän und führte zu eklogitfazieller Metamorphose in piemont-ligurischen Ophioliten, in den "Internmassiven", in Valais-Ophiolithen sowie in Einheiten des distalen europäischen Kontinentalrandes, namentlich der Adula-Decke.

1. Introduction

The 2nd Workshop on Alpine Geology, held in Basel in January, 1995, brought a most interesting exchange of ideas between geologists working in different parts of the Alps. Once more it became evident that the eastern part, east of a line from Bodensee (Lake Constance) to Lago di Como, appears fundamentally different from the western part, regarding structure and tectonometamorphic evolution. As a consequence, "western" and "eastern" views of the Alps diverged substantially.

The western part of the orogen, including the Western, Central and parts of the Southern Alps, is generally regarded as resulting from the subduction of the Penninic ocean (or oceans) and the following continental collision between Europe and the Apulian (Adriatic) continent. Different opinions exist about the age and paleogeographic position of subduction and collision (Cretaceous vs. Tertiary, one or two sites of subduction), partly due to conflicting radiometric age determinations of high-pressure metamorphic rocks (e.g. Paquette et al. 1989, Tilton et al. 1991). In the eastern part of the Alps, however, Cretaceous orogeny including high-pressure metamorphism is well established (e.g. Thöni & Jagoutz 1992, 1993). As an interesting new perspective, some authors proposed that Cretaceous orogeny was not related to subduction and collision along the Penninic oceans, but along another ocean originally located more internally in respect to the Penninic oceans, the Meliata-Hallstatt ocean (e.g. Thöni & Jagoutz 1993, Neubauer 1994, Neubauer et al. 1995b). This hypothesis elegantly explains the occurrence of Cretaceous high-P metamorphic terranes within the Austroalpine realm: The Austroalpine was part of the lower plate during this early collision and was overridden by another continental plate from the South or East. How can this hypothesis be reconciled with the tectonic history of the Central and Western Alps? Since the Alps are one mountain range, the two parts cannot have evolved completely independently.

The boundary zone between the Eastern and Central Alps in Eastern Switzerland (Graubünden) and Northern Italy forms a key area for reconciling the tectonic histories of the two contrasting parts of the Alps. In the first part of the present paper, we will therefore review Mesozoic rifting and paleogeography in this area, and compare this evolution with that in other parts of the Alps. In the second part, we will show how two orogenies, of Cretaceous and Tertiary age, are superimposed in the Austroalpine-Penninic boundary zone of Graubünden. Finally, the age and tectonic setting of high-pressure metamorphism in the Alps will be discussed in the framework of paleogeography. It will be emphasized that the stages of the preorogenic and orogenic evolution, like rifting, oceanic spreading, subduction, collision, and collapse, did not occur everywhere at the same time, but at completely different times in the different paleogeographic realms of the Alps (see also Oberhänsli 1994).

2. Mesozoic rifting and paleogeography

2.1 General remark

Ophiolite units occur in different structural levels of the Alpine nappe pile. This fact may be explained in two ways. The "one-ocean concept" assumes that a single ocean existed and was consumed by subduction, and that the multiple sutures presently observed result from tectonic processes like out-of-sequence thrusting and nappe refolding, either in an accretionary-wedge setting or after continental collision (e.g. Polino et al. 1990). In contrast, the "multi-ocean concept" assumes that the different ophiolite sutures represent different oceanic basins (e.g. Platt 1986). Structural and stratigraphic studies of Mesozoic passive continental margin units and ophiolites are of great importance for solving this controversy. On one hand, such studies help deciphering whether oceanic and continental units represent originally neighbouring domains, or were only juxtaposed tectonically. We will show in the following that fossil ocean-continent transitions can be reconstructed in some instances, indicating that more than one oceanic basin existed in the Alpine region. On the other hand, such studies have demonstrated that the Alpine oceanic basins were, at least in part, no large Atlantic-type oceans, but smaller-scale basins, often floored by exhumed subcontinental mantle rocks instead of typical oceanic lithosphere (Lemoine et al. 1987). Therefore, the term "ocean", as used in the following, simply refers to a basin floored by oceanic crust and/or exhumed mantle, irrespectively of the width of the basin.

2.2 *Late Jurassic-Early Cretaceous rifting and formation of the Valais basin*

In Graubünden the remnants of two Penninic oceanic basins are preserved. The northern one (Valais basin) is represented by Bündnerschiefer units (Pl. 1: "NPB"). These occur in two large outcrop areas, east of the Aar massif and in the Engadine window. The Bündnerschiefer form a large volume of calcareous shales and arenites, subdivided into several thrust sheets. In the main outcrop area the Bündnerschiefer grade into flysch deposits which are lithologically not very different from the Bündnerschiefer and are dated as Late Cretaceous to Early Tertiary (up to Early Eocene; Nänny 1948, Ziegler 1956, Eiermann 1988). Steinmann (1994), using lithological criteria and chemical stratigraphy, concluded that most of the Bündnerschiefer are Cretaceous in age. Everywhere these series of Bündnerschiefer are allochthonous, the base of several individual thrust sheets being formed by mélange zones. Intercalated basic rocks, often pillow basalts, indicate deposition either on oceanic or on thinned continental crust. Geochemical criteria (Dürr et al. 1993, Steinmann 1994) suggest a partly oceanic basement.

The Briançonnais terrane, a continental fragment south of the Valais basin, is represented by two basement-and-cover nappes (Tambo and Suretta) and by the detached cover nappes of Schams, Falknis, and Sulzfluh in the Graubünden area. The Mesozoic strata of these nappes are in typical Briançonnais or Subbriançonnais facies ("Subbriançonnais" in a paleogeographic sense refers to the northern margin of the

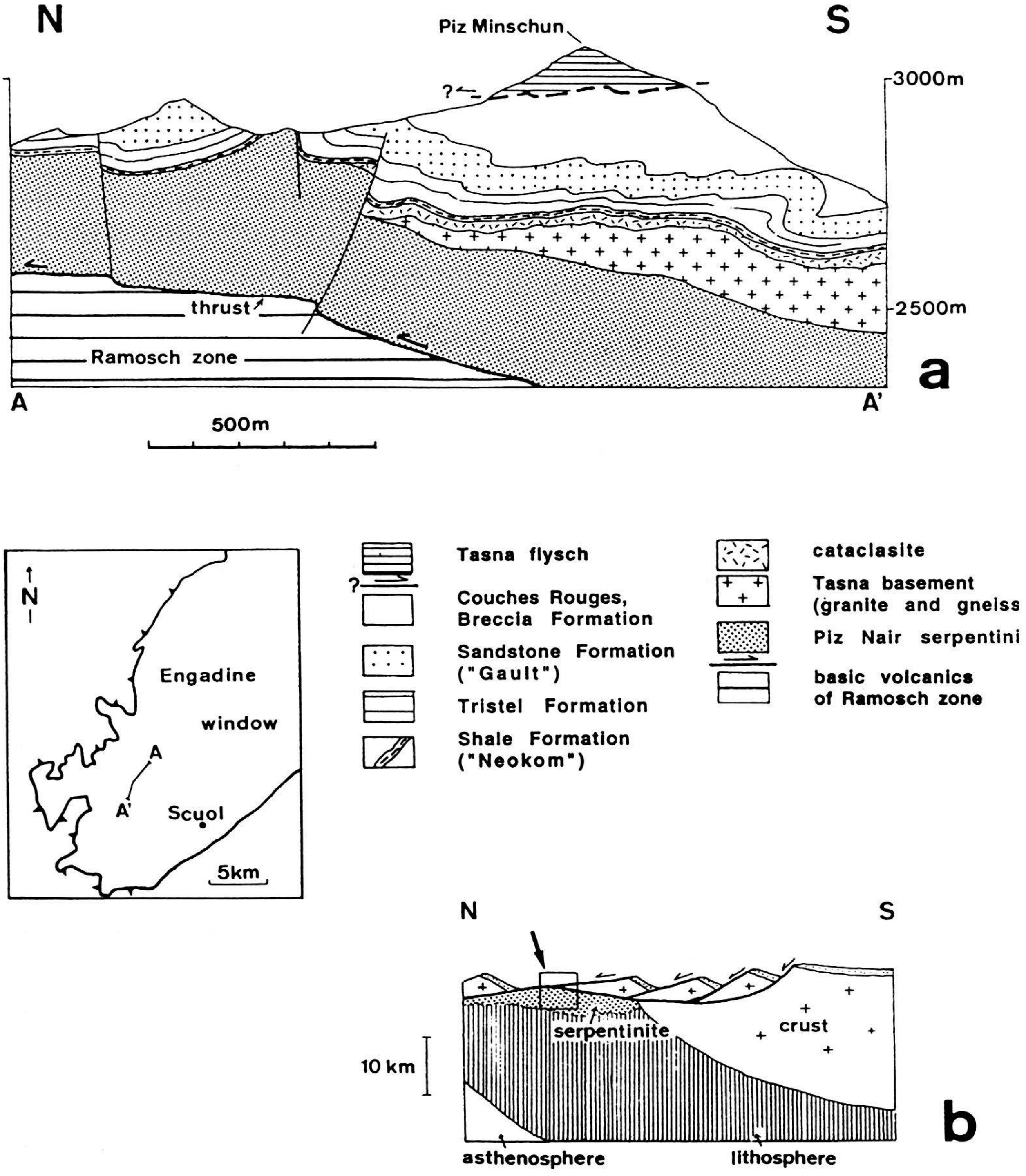


Fig. 1. Fossil ocean-continent transition between the Briançonnais terrane and the Valais ocean in the Tasna nappe. (a), cross-section of Piz Minschun area; (b), reconstruction for Early Cretaceous time. Arrow and box in (b) indicate the position of the Piz Minschun cross section (a). After Florineth & Froitzheim (1994).

Briançonnais terrane). In eastern Switzerland both paleogeographical domains are characterized by important hiatuses and breccia formations (Rück 1995). The Tasna nappe in the Engadine window is also interpreted to originate from the Briançonnais terrane (Trümpy 1972). A recent study in the Tasna nappe (Florineth 1994, Florineth & Froitzheim 1994) revealed a preserved transition between continental crust of the Briançonnais terrane and oceanic crust of the Valais basin. In the area of Piz Minschun (Fig. 1), a northward-tapering wedge of granitic-gneissic basement rocks is underlain by serpentinite (Piz Nair serpentinite) and uncomformably overlain by Cretaceous sediments, including thin "Neocomian" shale, Upper Barremian to Lower Aptian turbiditic limestone (Tristel Formation, Schwizer 1983), Aptian-Albian "Gault" sandstone and black shale, and Upper Cretaceous Couches Rouges with polymict breccias. Towards the North, the same sedimentary sequence directly rests on the Piz Nair serpentinite originally representing subcontinental lherzolite according to mineral chemistry (Florineth 1994). Towards the contact with the Cretaceous sediments, both the granitic-gneissic basement and the serpentinite show intense cataclastic deformation (chloritic breccia and ophicalcite, respectively). The Cretaceous sediments rest with a depositional contact on these cataclastic rocks. The contact is interpreted as a rifting-related, extensional detachment fault, the hanging wall of which had been completely removed by progressive displacement before the sediments were deposited on top (Fig. 1b). The Piz Nair serpentinite represents a "peridotite ridge" of tectonically exhumed, subcontinental mantle material, comparable to the one found along the west Iberian margin of the Atlantic (Boillot et al. 1987). Directly underlying the Piz Nair serpentinite along an Alpine, top-north directed thrust fault, pillowed basalts, representing a more central part of the Valais ocean, crop out in the Ramosch zone. These pillowed basalts in turn overlie a mélange zone (Roz-Champatsch zone) situated above North Penninic Bündnerschiefer.

The relations observed in the Tasna nappe directly confirm earlier suggestions regarding the Valais basin (Kelts 1981, Stampfli 1993, Steinmann 1994): First, the Valais basin was indeed floored, at least in part, by oceanic crust. Second, the rifting involved exhumation of subcontinental mantle by extensional faulting. Third, the continental break-up in this part of the Valais basin occurred in the Early Cretaceous, prior to the Late Barremian. Apart from the Tasna nappe, the rifting phase preceding the break-up is recorded by Upper Jurassic breccia deposits in the Falknis nappe (Falknis Breccia, Trümpy 1916, Gruner 1981) and, probably, by parts of the Vizan Breccia in the Schams nappes (Schmid et al. 1990, Rück 1995). The Vizan Breccia represents the entire time interval from Middle Jurassic to Early Cretaceous (Rück 1995). The lower part of this breccia formation (Middle Jurassic) was formed during the rifting phase of the Piemont-Liguria ocean, and the upper, Upper Jurassic-Lower Cretaceous part during the Valais rifting.

Thus, the Briançonnais units of Graubünden were rifted away from the European continent during the Late Jurassic to Early Cretaceous, which is in accordance with the larger-scale considerations of Frisch (1979) and Stampfli (1993). These authors connected the opening of the Valais ocean with opening of the Atlantic west of the Iberian plate, opening of the Bay of Biscay, and formation of transtensional basins in the Pyrenees. The Briançonnais became part of a microcontinent including Iberia, Sardinia, and Corsica (Fig. 2).

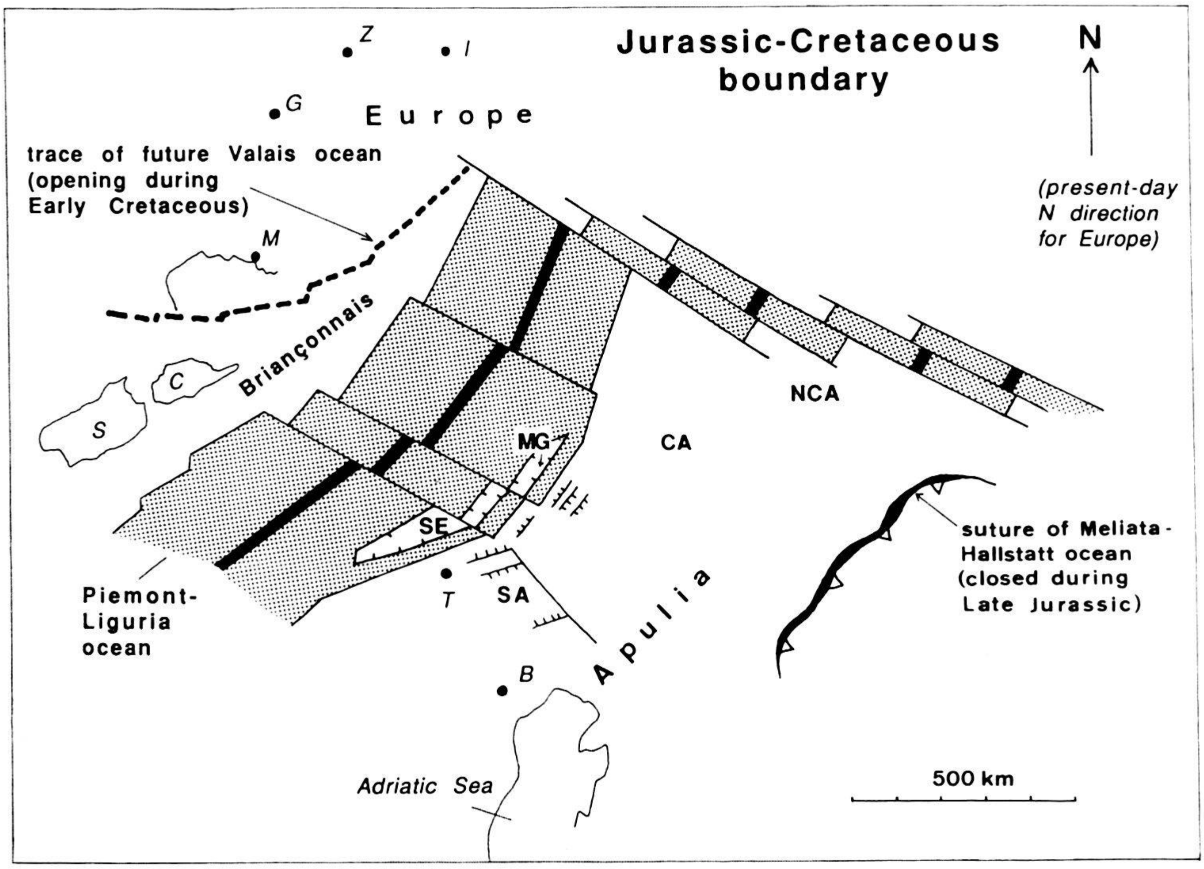


Fig. 2. Paleogeography in the Alpine realm reconstructed for the Jurassic-Cretaceous boundary time. CA, Central Austroalpine; MG, Margna; NCA, Northern Calcareous Alps; SA, Southern Alps; SE, Sesia; B, Bologna; C, Corsica; G, Geneva; I, Insbruck; M, Marseille, S, Sardinia; T, Torino; Z, Zürich. After Dercourt et al. (1986), Stampfli (1993), and Schmid et al. (in press a).

2.3 Extension of the Valais ocean towards west and east

Towards west, the main outcrop area of Bündnerschiefer in Graubünden is connected in a rather complicated way with the Valais zone in the upper Rhône valley (SW of Aar massif in Pl. 1). In Graubünden, the suture of the Valais ocean, from which the Bündnerschiefer was expelled, is found in the Misox zone between the Tambo nappe (Briançonnais) above and the Adula nappe below (Schmid et al. 1990). From here, the suture can be followed between the different Penninic gneiss nappes of the Lepontine area in the way depicted in Plate 1, to join the Valais zone in the West. As a consequence, the deeper Penninic gneiss nappes (Adula, Simano, Leventina-Lucomagno, Antigorio etc.) represent the former southern margin of the European continent towards the Valais ocean. At least parts of them formed the original basement of the Helvetic nappes (Schmid et al. in press b). From the upper Rhône valley, the Valais zone can be followed further southwest to Savoie where it wedges out for still unknown reasons, between the Briançonnais units and the external massifs (European crust).

Towards east, the paleogeographic relations are more difficult to reconstruct since the Penninic nappes are largely covered by the huge thrust mass of Austroalpine units. Penninic units first reappear in the Tauern window. The deepest unit of this window is represented by continental crust of the Zentralgneis cores with their autochthonous cover (e.g. Hochstegen limestone). These are overlain by detached basement and cover nappes, also of continental origin. The Zentralgneis, together with these continental nappes, forms the Venediger nappe (Frisch 1976). Above follow thick Bündnerschiefer series with intercalated basic volcanics (Glockner nappe), strongly similar to the Valais Bündnerschiefer of Graubünden. Along the southern border of the window and overlying the Glockner nappe, remnants of Piemont-Ligurian oceanic crust are mixed with Austroalpine slivers to form the mélange of the Matrei zone. At present, most authors regard the Venediger nappe as Middle Penninic (Briançonnais, e.g. Frisch 1979), and the Glockner nappe and Matrei zone as South Penninic (Piemont-Ligurian). It was noticed, however, that the facies of the cover of the Venediger nappe is untypical for the Briançonnais units (e.g. Faupl & Wagreich 1992, p. 392). Lammerer (1988) demonstrated that the lithostratigraphy of the Zentralgneis cover is very similar to that of the Helvetic nappes in Switzerland, probably reaching up into the Turonian. Therefore, we prefer to correlate (as proposed by Trümpy 1988) the Venediger nappe with the units representing the European margin in Switzerland (Helvetic nappes and lower Penninic nappes of the Lepontine area), and the Glockner nappe with the Valais units, that is, the Bündnerschiefer of Graubünden. According to this working hypothesis, only the Matrei zone would correspond to the Piemont-Ligurian units of the Central and Western Alps. Since no continental nappes occur between the Glockner nappe and the Matrei zone, Briançonnais units would be completely missing in the Tauern cross section. This could be explained in two ways: Either, the front of the Briançonnais nappes is south of the Tauern window, that is, the Briançonnais was mostly or completely subducted, or, the Briançonnais as a paleogeographic domain ended primarily between the Engadine window and the Tauern window, and the Valais and Piemont-Ligurian basins merged eastward into a joint basin (Fig. 2).

Penninic units also occur in a narrow stripe along the northern front of the Eastern Alps. Mélange zones, derived from the Piemont-Ligurian basin and the adjacent, distal margin of the Apulian plate, directly underlie the Northern Calcareous Alps at their northern margin (Walsertal zone, Winkler 1988, and Ybbsitz zone, Decker 1990). These mélanges are in turn underlain by the Rhenodanubian flysch whose paleogeographic affiliation is still controversial. On one hand, strong facies analogies exist between the Upper Cretaceous to Lower Tertiary part of the Rhenodanubian flysch and the Wägital, Schlieren and Gurnigel flysch units further west, for which a Piemont-Ligurian origin is assumed (Winkler et al., 1985), and marked differences exist between the Rhenodanubian flysch and the Bündnerschiefer and overlying flysch in Graubünden. On the other hand, Hesse (1973) proposed, using sedimentological criteria, that the western part of the Rhenodanubian flysch was deposited in a basin north of the Tasna and Falknis nappes, that is, north of the Briançonnais. In Plate 1, we follow Hesse and other authors (e.g. Winkler 1988, Faupl & Wagreich 1992) and correlate the Rhenodanubian flysch with the Valais basin. The solution of the problem may again be that the Briançonnais terrane ended east of Graubünden, and that Valais and Piemont-Ligurian basin merged into one single Penninic basin (e.g. Fig. 1 in Laubscher & Bernoulli 1982).

2.4 *Early to Middle Jurassic Piemont-Ligurian rifting in the Graubünden area*

The passive margin between the Apulian continent and the Piemont-Ligurian ocean is preserved in the Austroalpine and Upper Penninic nappes of Graubünden and adjacent Italy and in the Southern Alps (Trümpy 1975, Weissert & Bernoulli 1985, Froitzheim & Eberli 1990, Bernoulli et al. 1993, our Fig. 2, 3). Piemont-Ligurian units in Graubünden include the Arosa zone along the base of the Austroalpine to the North, and the Platta nappe to the South. In the southern part, the Penninic-Austroalpine boundary is complicated: The Margna-Sella nappe, of continental origin and with a Mesozoic facies similar to the one of the Austroalpine units, is sandwiched between two units of Piemont-Ligurian ophiolites: the southern extension of the Platta nappe above and the Lizun-Forno-Malenco ophiolites below. All these units suffered their main deformation in the Late Cretaceous and were welded to the Austroalpine margin at this time (Liniger & Nievergelt 1990). This is not the case for another Piemont-Ligurian ophiolite unit, the Avers Bündnerschiefer, because the latter presently occurs in a deeper structural level, separated from the Austroalpine by Tertiary flysch (Arblatsch flysch, Ziegler 1956, Eiermann 1988). The Piemont-Ligurian units of Graubünden are characterized by the sediment sequence radiolarite – Calpionella limestone – Palombini shale and limestone (Weissert & Bernoulli 1985). This sequence is very similar to the cover of oceanic units in Liguria and in the Western Alps. Using this analogy, the age of the radiolarite, the first sediment overlying the oceanic crust, can be assumed to be the same as in Liguria and in the Western Alps: late Middle Jurassic to Late Jurassic (e.g. De Wever et al. 1987).

Sedimentological (Eberli 1988, Furrer 1993) and structural work (Froitzheim & Eberli 1990, Conti et al. 1994, Manatschal 1995) in the Austroalpine nappes have shown that the extension direction during the rifting of the Austroalpine-Penninic passive margin was approximately east-west in present-day coordinates. Rifting proceeded in two phases. The first phase occurred in the Liassic, from Hettangian to Pliensbachian, approximately. During the first phase, east-dipping normal faults bounding half-graben formed in the proximal, continentward part of the margin (Bernina, Ela and Ortler units, Fig. 3). During the second rifting phase, beginnng in the Toarcian and ending with continental breakup in the Middle Jurassic (Bajocian – Bathonian), westward-dipping normal faults formed in the distal part, near the future ocean. These included large-displacement detachment faults (Froitzheim & Eberli 1990, Manatschal 1995). A typical "outer basement high" formed between the west-dipping and the east-dipping fault systems, in the area that later became the Bernina nappe (Fig. 3).

2.5 *The Margna-Sella extensional allochthon*

The position of the Margna-Sella nappe between two ophiolite sutures can either be explained by a primary complication of the passive margin, or by subsequent Alpine deformation complicating a simple primary situation. In their studies of the structural evolution of the Margna nappe, Liniger (1992) and Spillmann (1993) found no evidence for the second solution, and favoured a primary margin complication. Froitzheim & Manatschal (in press) propose that the Margna-Sella nappe represents an extensional allochthon, separated from the Austroalpine margin by detachment faulting (Fig. 3). Accordingly, the southern part of the Platta nappe, between the Austroalpine and the Margna-Sella

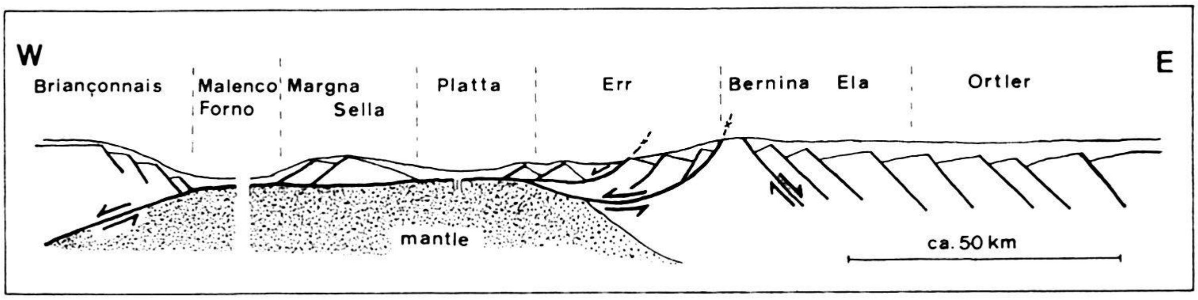


Fig. 3. Reconstructed cross section of the Piemont-Liguria basin in the Central and Eastern Alps, at the time of continental break-up (Middle Jurassic), from Froitzheim et al. (1994). For further explanation see text.

nappe, would not represent typical oceanic crust formed at a mid-ocean ridge, but a "window" of subcontinental mantle lithosphere where basaltic volcanism occurred owing to the stretching of this lithosphere. Complete exhumation of subcontinental mantle in the Malenco unit (Trommsdorff et al. 1993) and in the Platta nappe (Manatschal 1995, Froitzheim & Manatschal in press) is explained by progressive displacement along a system of west-dipping detachment faults active during the second rifting phase. The hanging wall of the detachment system was represented by the Briançonnais (still attached to Europe at that time), which moved westward away from the Austroalpine units and left the Margna-Sella klippe back on the surface of the exhumed mantle. Ongoing separation of the Apulian plate from Europe along the Piemont-Ligurian basin may have resulted in the installation of a mid-ocean ridge and the formation of oceanic lithosphere west of the Margna-Sella allochthon. The latter remained close to the Apulian margin.

2.6 *The Apulian margin in the Southern Alps*

After correcting for the effects of Alpine folding, the trend of the Jurassic rift-related faults in the Austroalpine is approximately north-south in present-day coordinates (Froitzheim & Eberli 1990, Conti et al. 1994, Manatschal 1995). Since the boundary between Austroalpine units and Southern Alps (Insubric line) strikes east-west, the southern prolongation of the Austroalpine – Penninic passive margin can be found in the Southern Alps (Weissert & Bernoulli 1985, Bernoulli et al. 1993). The proximal margin basins of the Austroalpine Ortler and Ela nappes have an equivalent in the Generoso and Monte Nudo basins of Lombardy. There, the timing and geometry of normal faulting are the same as in the Central Austroalpine of Graubünden. Major Liassic normal faults in Lombardy, like the Lugano fault (Bernoulli 1964, Bertotti 1991) trend east-northeast, which implies that little post-Liassic relative rotation occurred between the western Austroalpine units in Graubünden and the Southern Alps in Lombardy. The outer basement high of the Bernina nappe is found again in the eastern part of the Canavese zone, and the distal part of the margin in the western Canavese zone (Bernoulli et al. 1993).

In the context of Jurassic rifting and ocean formation, the westernmost part of the Southern Alps merits particular interest. The western Canavese zone, the most distal edge of the former Apulian passive margin, is in contact with the Sesia nappe across the

Insubric line which here trends NNE-SSW. The Sesia nappe, together with the Dent Blanche nappe further to the northwest, is generally regarded to represent the Austroalpine in this western part of the Alps, because it overlies the Piemont-Ligurian ophiolites of the Zermatt-Saas zone (e.g. Dal Piaz et al. 1977). However, several authors (e.g. Mattauer et al. 1987) have insisted that ophiolites occur in a structural position between the Canavese zone and the Sesia nappe. This is the case for slivers of radiolarite and serpentinite in the Torrente Levone profile (Elter et al. 1966). Furthermore, the Lanzo peridotite body, representing former ocean floor according to Bodinier (1988), is found in a position to the southeast of and above the Sesia nappe (Blake et al. 1980). For such reasons, Aubouin et al. (1977) and Mattauer et al. (1987) placed the suture of the Piemont-Liguria ocean between the Southern Alps and Sesia, and not between Sesia and the Briançonnais. As in Graubünden, the problem of the double suture can be solved by assuming that the Sesia and Dent Blanche nappes represent an extensional allochthon close to the Apulian margin, similar to or even connected with the Margna allochthon in Graubünden (Froitzheim & Manatschal in press). This assumption is expressed in Figure 2. In fact, strong lithologic similarities exist between Margna nappe and Sesia/Dent Blanche (Staub 1917). In particular, structurally and geochemically very similar gabbro intrusions occur in both units (Stünitz 1989, p. 224).

As an important implication of this hypothesis, we do no longer attribute the Sesia and Dent Blanche nappes to the Austroalpine in the strict sense, which means that there are no Austroalpine units preserved in the Western Alps. We propose that this lack of Austroalpine units results from paleogeography rather than from erosion. The trend of the Apulian margin was strongly oblique with respect to the present mountain chain. This is certainly a prime reason for the different tectonic evolutions in the Western and Eastern Alps.

We arrive at the paleogeographic picture of a continuous Apulian passive margin in the Southern Alps and in the Austroalpine, bordered to the northwest by a stripe of marginal oceanic lithosphere and an extensional allochthon (Margna, Sesia) of continental crust. This reconstruction is remarkably similar to the one already proposed by Compagnoni et al. (1977, their Fig. 3). As we will see below, the situation is of great importance for the orogenic evolution of the Alps, because it explains why the Sesia unit could be subducted under the Apulian margin in the Cretaceous, before the closure of the Piemont-Ligurian ocean.

Due to extremely intense Alpine deformation, the reconstruction of the opposing, northwestern margin of the Piemont-Ligurian ocean is more difficult. Some authors (e.g. Milnes et al. 1981, Platt 1986) assume that an oceanic space existed between the Penninic "internal massifs" (Monte Rosa, Gran Paradiso, Dora Maira) and the Briançonnais. The corresponding suture would in this case be represented by the Antrona ophiolites (Pl. 1). According to the majority of authors, however, the internal massifs represent the former margin between Briançonnais and Piemont-Liguria ocean (e.g. Lemoine et al. 1986), and the position of the Antrona ophiolites would have to be explained by Alpine out-of-sequence thrusting or nappe folding. This interpretation is adopted here (Pl. 1).

2.7 *Triassic paleogeography and the Meliata-Hallstatt ocean*

The distribution of Triassic facies in the Southern Alps and in the Northern Calcareous Alps (NCA) is characterized by a trend from terrestrial to marginal marine conditions in the northwest to open marine conditions in the southeast (see Fig. 4 in Laubscher & Bernoulli 1977, and Prey 1980, p. 27). This trend towards open marine conditions is directed away from the later-forming Piemont-Ligurian ocean (located northwest of the Austroalpine) and is obviously unrelated to the formation of this ocean. Therefore, Lein (1987) interpreted the Triassic of the NCA as recording a passive-margin evolution related to an ocean located southeast of the Austroalpine realm.

It was long thought that, in the Triassic period, the oceanic lithosphere of the Tethys did not reach further west than Turkey (e.g. Trümpy 1982), and in any case not into the Alps. However, Middle Triassic radiolarite associated with ophiolites (serpentinite, gabbro, pillow basalt) was found in the Meliata unit of the western Carpathians (Kozur & Réti 1986). Recently, Mandl & Ondrejickowa (1991) and Kozur & Mostler (1992) found Middle Triassic to Carnian radiolarite, partly associated with slivers of serpentinite, also in the eastern part of the NCA. These authors assume that a Triassic ocean, called Meliata-Hallstatt ocean (Kozur 1991), reached into the eastern NCA. Even remnants of the opposing, southern margin of the Meliata-Hallstatt ocean were identified in this area ("Süd-Rudabanyaikum", Kozur & Mostler 1992), but the tectonic situation still seems quite unclear.

Remnants of a pre-Jurassic ocean were also assumed to occur in the Central Austroalpine units, that is, in the basement-dominated nappes between the NCA and the Southern Alps, east of the Tauern window (Thöni & Jagoutz 1993). The rocks under question are eclogites found within polymetamorphic basement of the Koralpe and Saualpe east of the Tauern window. The eclogitic metamorphism of these rocks in assumed to be Cretaceous in age. An unaltered gabbro relic yielded a protolith age of 275 ± 18 Ma (Thöni & Jagoutz 1993) and exhibits the geochemical characteristics of a MORB-type source (Miller et al. 1988). Therefore, Thöni & Jagoutz (1993) concluded that the basic rocks are remnants of a Permian oceanic crust. The association of the eclogites with polymetamorphic continental basement and the lack of any pelagic sediments, however, sheds severe doubt on the oceanic nature of the rocks. Permian gabbro intrusions in the lower crust are widespread throughout the Alps (Dent Blanche nappe, Dal Piaz et al. 1977, Ivrea zone, Voshage et al. 1990, Margna nappe, Hansmann et al. 1995) and are not necessarily related to oceanic lithosphere. Instead, these gabbros probably intruded during the transtensional collapse of the Variscan orogen. We conclude that the existence of Permian ophiolites in the Eastern Alps remains to be proven.

The break-up of the Meliata-Hallstatt ocean is assumed to have occurred during the Middle Triassic. This is the age of the oldest pelagic sediments found in association with ophiolites in the Meliata unit (Kozur 1991). The paleogeography of this ocean is highly debated. According to Kovacs (1982) the Meliata-Hallstatt ocean may be correlated with the Vardar ophiolites in the Hellenides. This correlation is strictly rejected by Kozur (1991). Closure of the Meliata-Hallstatt ocean already occurred in the Late Jurassic (Oxfordian; Kozur 1991). At this time, the Austroalpine – West Carpathian block collided with the Tisia microplate, the "Pannonian median massif" of the older literature (see Kovacs 1982).

2.8 Did the Meliata-Hallstatt ocean extend westwards between the Austroalpine and the Southern Alps?

This question is of fundamental interest for the paleogeography of the Alps and for the reconstruction of their orogenic evolution. In the Graubünden transect, those units that originated – in our opinion – from the Apulian plate, can be grouped into three complexes: The Southern Alps south of the Insubric line, the Central Austroalpine nappes, located between the Insubric line and the southern border of the NCA, and the Northern Calcareous Alps themselves (Pl. 1). Channell et al. (1992) proposed a western extension of the Meliata-Hallstatt ocean between the NCA and the Southern Alps. Accordingly, the Austroalpine realm would not have been part of the Apulian plate, as classically assumed, but would represent an independent plate, the Austroalpine plate.

There are two possible sutures along which the remnants of such a Triassic ocean could have been subducted: The Insubric line, and the boundary between Central Austroalpine and NCA. For the following reasons the first solution has to be excluded right away:

(1) No remnants of ophiolites exist along that part of the Insubric line which separates South Alpine from Austroalpine units.
(2) The Triassic rocks to both sides of the Insubric line show the same trend of westward shallowing. They are generally developed in a terrestrial to marginal marine facies in the westernmost parts of the Austroalpine realm (Furrer 1985, Naef 1987) and of the Southern Alps (Laubscher & Bernoulli 1977, Fig. 4). This is also the case in the immediate vicinity of the Insubric line.
(3) As mentioned above, the domains of the Jurassic-age Apulian passive margin are virtually identical in the Central Austroalpine of Graubünden and in the Southern Alps. It is highly improbable that a later, Jurassic passive margin would have formed across a Triassic ocean without changing its geometry.

The second possibility is unlikely as well. In the eastern part of the Eastern Alps, the remnants of the Meliata-Hallstatt ocean do in fact occur close to the southern boundary of the NCA (Pl. 1), the Triassic facies in the southernmost units of the NCA being more pelagic than in the Central Austroalpine units to the South. Going towards west, however, all indications for an oceanic suture are lost. The Triassic facies in the NCA becomes increasingly shallow-marine westward. At the western end of the Austroalpine nappes, comparable Triassic facies zones occur in the Central Austroalpine and in the NCA (Furrer 1993). Therefore, if an ocean had existed between the NCA and the Central Austroalpine, this ocean would have ended towards west, as depicted by Thöni & Jagoutz (1993). Such ending leads to severe kinematic problems, in that spreading needs to be transferred by a transform fault to another ocean, for which there is also no evidence in the Eastern Alps. In conclusion, the boundary between Central Austroalpine and NCA does probably not represent an oceanic suture but an Alpine, sinistral strike-slip zone along which the nappes of the internal eastern NCA with their pelagic facies and remnants of the Meliata-Hallstatt suture were transported relatively westward and juxtaposed to the Central Austroalpine units with their less pelagic facies (cf. Fig. 13 in Laubscher 1991).

We come to the conclusion that an extension of the Meliata-Hallstatt ocean between the Austroalpine realm and the Southern Alps is improbable, and that, within the Alps, this Triassic ocean was unconnected to the Piemont-Ligurian ocean. Such a connection between the two oceans may, however, have existed further to the East in the Carpathian region.

In summary, the paleogeographic evolution of the Alpine realm in Mesozoic times is controlled by the sequential formation of three basins which were at least partly underlain by oceanic crust and/or exhumed mantle. The most internal one is the Meliata-Hallstatt basin that opened in the Middle Triassic. The Piemont-Ligurian basin opened next, in the Middle Jurassic, and the break-up in the most external Valais basin occurred in the Late Jurassic to Early Cretaceous, when the Meliata-Hallstatt basin had already been closed.

3 Cretaceous orogeny

3.1 Cretaceous orogeny as recorded in the Austroalpine nappes in Graubünden

The Austroalpine units of Graubünden experienced a sequence of Alpine deformation phases that can be correlated on a regional scale (Froitzheim et al. 1994). The first, Late Cretaceous phase (Trupchun phase, ca. 100 to 80 Ma) involved westward (SW to NW) imbrication of basement-cover nappes and concomitant west- to northwest-facing folding (Ring et al. 1988, Handy et al. 1993, Froitzheim et al. 1994). The Trupchun phase affected not only Austroalpine units, but also the South Penninic Arosa, Platta and Malenco-Forno-Lizun ophiolites and the Margna extensional allochthon (Liniger & Nievergelt 1990). These units were accreted to the Austroalpine margin. Thrusting was accompanied by important sinistral transpressive shearing along an east-west striking lineament (Albula steep zone, approximately coinciding with the Ela nappe in Pl. 1). Still in the Late Cretaceous, the nappe edifice was stretched in an ESE-WNW direction, and ESE-dipping normal faults formed with displacements of up to 5 to 10 km (Ducan-Ela phase, ca. 80 to 67 Ma). This extensional phase separates the Cretaceous orogeny from the Tertiary orogeny, beginning in the Paleogene.

3.2 Large-scale framework of Cretaceous orogeny in the Austroalpine units

It was long assumed – and is still widely accepted – that Cretaceous orogeny in the Austroalpine resulted from southeastward subduction of the Piemont-Ligurian oceanic lithosphere under the Apulian margin, and the formation of an accretionary wedge above this subduction zone. This model has only recently been challenged (e.g. Thöni & Jagoutz 1993, Neubauer 1994). There are, in fact, strong arguments against it:

(1) High-pressure metamorphism is generally assumed to occur in the downgoing slab during subduction or in the lower plate during continent collision. The Cretaceous eclogites of the Austroalpine, however, are located in the hanging wall of the assumed subduction zone (Neubauer 1994).

(2) On the scale of the entire Austroalpine realm, thrusting propagated from E to W (or SE to NW). In the middle part of the NCA, the chromite-bearing, clastic Rossfeld

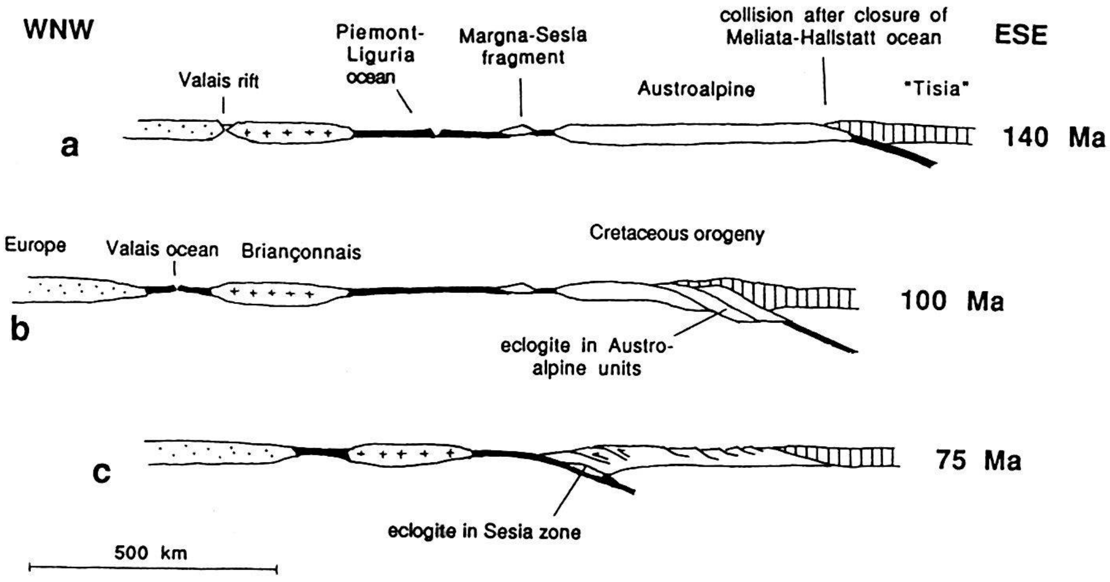


Fig. 4. Diagrammatic cross-sections showing the proposed sequence of events during the Cretaceous. Note that the sections are oriented WNW-ESE, parallel to the main direction of Cretaceous-age thrusting in the Austroalpine.

formation of Valanginian-Hauterivian age was deposited in a trench at the foot of an accretionary wedge (Faupl & Tollmann 1979), indicating orogenic shortening already in the Early Cretaceous. In contrast, in the westernmost part of the Austroalpine, pelagic sedimentation without indications for thrusting continued into the Upper Cretaceous (Cenomanian to possibly Early Turonian in the Ortler zone, Caron et al. 1982). Consequently, orogenic activity began much later (only after 90 Ma) in the westernmost part of the Austroalpine which paleogeographically is closest to the Piemont-Ligurian ocean (see also Neubauer 1994, documenting the same trend). Had the Cretaceous orogeny in the Austroalpine realm resulted from subduction of the Piemont-Ligurian ocean, one could hardly imagine that thrusting would have started far away from this ocean and then advanced towards the ocean.

(3) Intrusion of basanitic "Ehrwaldite" dykes in the NCA at 100 Ma (Albian) precludes the existence of a subducting slab beneath the NCA at that time (Trommsdorff et al. 1990).

For these reasons, the interpretation of the Austroalpine thrust belt resulting from continent collision after the closing of the Meliata-Hallstatt ocean and propagating northwestward into the lower plate (Neubauer 1994) is more convincing than the classical model. It is adopted in our Fig. 4 (a, b).

Although Austroalpine and South Alpine units belong to the same Jurassic-age passive margin, their tectonic evolutions diverge from the Cretaceous period onward. Cretaceous events comparable to the ones found in the Austroalpine are not reported from the Southern Alps. It is true that some thrusting and folding of probably Late Cretaceous age (Zanchi et al. 1990) occurred in the Southern Alps west of the Giudicarie line. Differently from the Austroalpine, however, these thrusts were directed towards the South (Schönborn 1992) and were not nearly as important as the west-directed thrusts in the Austroalpine realm. In the area of the Dolomites, that is, the Southern Alps east of the Giudicarie line, Cretaceous thrusting is apparently missing altogether (Doglioni & Bosellini 1987).

To explain this difference, we propose that the Tertiary-age, dextral Insubric line had a Cretaceous-age forerunner which acted as a sinistral tear-fault, separating a west-directed thrust belt to the north (Austroalpine) from a more stable area to the South (Southern Alps). The sinistral Albula steep zone (see above) is a smaller-scale analogue of this tear-fault. Other important sinistral strike-slip faults of Late Cretaceous age, striking SW-NE, were found by Neubauer et al. (1995a) in the Austroalpine units east of the Tauern window. The westward movement of Austroalpine thrust sheets relative to the Piemont-Ligurian ocean implies that dextral strike-slip movement or oblique convergence prevailed along the northern, more east-west-striking margin of the Austroalpine. Thus, the Austroalpine belt appears as a westward advancing thrust system bounded by strike-slip faults or transpressive zones both to the South and to the North.

3.4 Late Cretaceous subduction in the Piemont-Ligurian ocean

Although we explain Cretaceous orogeny in the Austroalpine units by westward propagation of a thrust wedge as a consequence of continental collision along the Meliata-Hallstatt ocean (in accordance with Neubauer 1994), we have to respect the fact that the subduction of Piemont-Ligurian lithosphere did begin in the Cretaceous. The onset of subduction is constrained by the sedimentary record, i.e., by the first occurrence of flysch-type sediments containing ophiolite detritus, which may be interpreted as being shed from an accretionary wedge. In the Piemont-Ligurian units of the Eastern Alps, this is difficult because ophiolite detritus found in these units may also have been shed from the suture of the Meliata-Hallstatt ocean. A more suitable area for dating the onset of subduction is Liguria, because this area was far from the Austroalpine thrust belt. The oldest detrital units containing ophiolite debris in Liguria are Campanian in age (Casanova complex, Elter 1993, p. 209). Elter (1993) proposes that ophiolitic detritism may have started earlier, already in the Albian, but that these sediments were later subducted. Onset of subduction in the Piemont-Ligurian basin in the Albian to Late Cretaceous would also be in accordance with the constraint imposed by the "Ehrwaldite" dykes in the NCA (see above). The subduction zone in Liguria was probably intra-oceanic and east-dipping during the Late Cretaceous, because an eastern sub-basin with partly oceanic substratum (external Ligurides) remainded open until the Tertiary (Hoogerdujn Strating 1991). Further north, in the Piemont region, this subduction zone had to be close to the Apulian margin (see Figs. 1 and 3 of Elter & Pertusati 1973), in order to allow for Late Cretaceous subduction of the Sesia continental fragment (Fig. 4c). Alternatively, two subduction zones may have been active in the Piemont-Ligurian basin, one intra-oceanic and one close to the Apulian margin (Avigad et al. 1993).

4. Tertiary orogeny

4.1 Tertiary orogeny as recorded in a cross section at the western margin of the Eastern Alps

Tertiary structures in the Austroalpine nappes in Graubünden record a change in the shortening direction in respect to Cretaceous orogeny. After the east-southeast-directed Late Cretaceous extension, renewed shortening began in the Early Tertiary (Blaisun phase, Froitzheim et al. 1994), recorded by the formation of east-southeast striking gentle folds and by north- to north-northeast directed thrusting of the Austroalpine – Upper Penninic nappe edifice, internally stacked during the Cretaceous, over deeper Penninic units. The direction of shortening within this relatively rigid nappe stack (orogenic lid in the sense of Laubscher, 1983) and the transport direction along the basal thrust over the deeper Penninic units (N to NNE) differed from the shortening direction during Cretaceous thrusting (W to NW) by about 90°. This change indicates a reorientation of plate movements.

We attribute the tectonometamorphic evolution within most of the Penninic nappes (with the exception of the Piemont-Liguria domain) to the Tertiary cycle. In particular we assume that collision between the Austroalpine and the Briançonnais occurred in this new framework of north-south directed shortening, starting in the early Paleocene (Fig. 5a and Schmid et al., in press b). During the Paleocene and Eocene, Briançonnais, Valais and distal European continental margin units were accreted to the orogenic lid (Fig. 5). This process began in the southernmost units and proceeded towards north (Schmid et al. in press b). The onset of the accretion process in the different units is constrained by the age of the youngest sediments. These are Paleocene on the southern margin of the Briançonnais in western Switzerland (Breccia nappe, Chessex 1959), Paleocene to possibly Eocene in the Briançonnais of eastern Switzerland (Falknis and Sulzfluh nappes, Allemann 1956), latest Paleocene to Early Eocene in the Valais units of eastern Switzerland (Arblatsch flysch, Eiermann 1988), and Late Eocene on the distal European margin (South Helvetic units, Herb 1988, Lihou 1995). All of the lower crustal and substantial volumes of the upper crustal material of the Briançonnais terrane and the distal European margin must have been subducted during this time. This follows from area-balanced profile reconstructions (Fig. 5 and Schmid et al., in press b) based on stratigraphic and structural data extensively discussed in Schmid et al. (in press a). Some of this subducted material was later exhumed to form the eclogites of the Adula nappe attributed to the distal European margin (Fig. 5a). Another result of this reconstruction is the large amount – about 500 km – of Tertiary N-S convergence between Europe and the Apulian plate. This is in agreement with plate tectonic reconstructions (Dewey et al. 1989).

The impressive amount of convergence is a corollary of the paleogeographic position inferred for the middle and lower Penninic basement nappes (Briançonnais for the Tambo and Suretta nappes, European margin for the Adula and all structurally lower nappes). Our reconstruction also implies that the eclogites found in the Adula nappe are of Tertiary age. Therefore the structural setting of these eclogites merits a brief discussion, while the geochronological evidence will be discussed later.

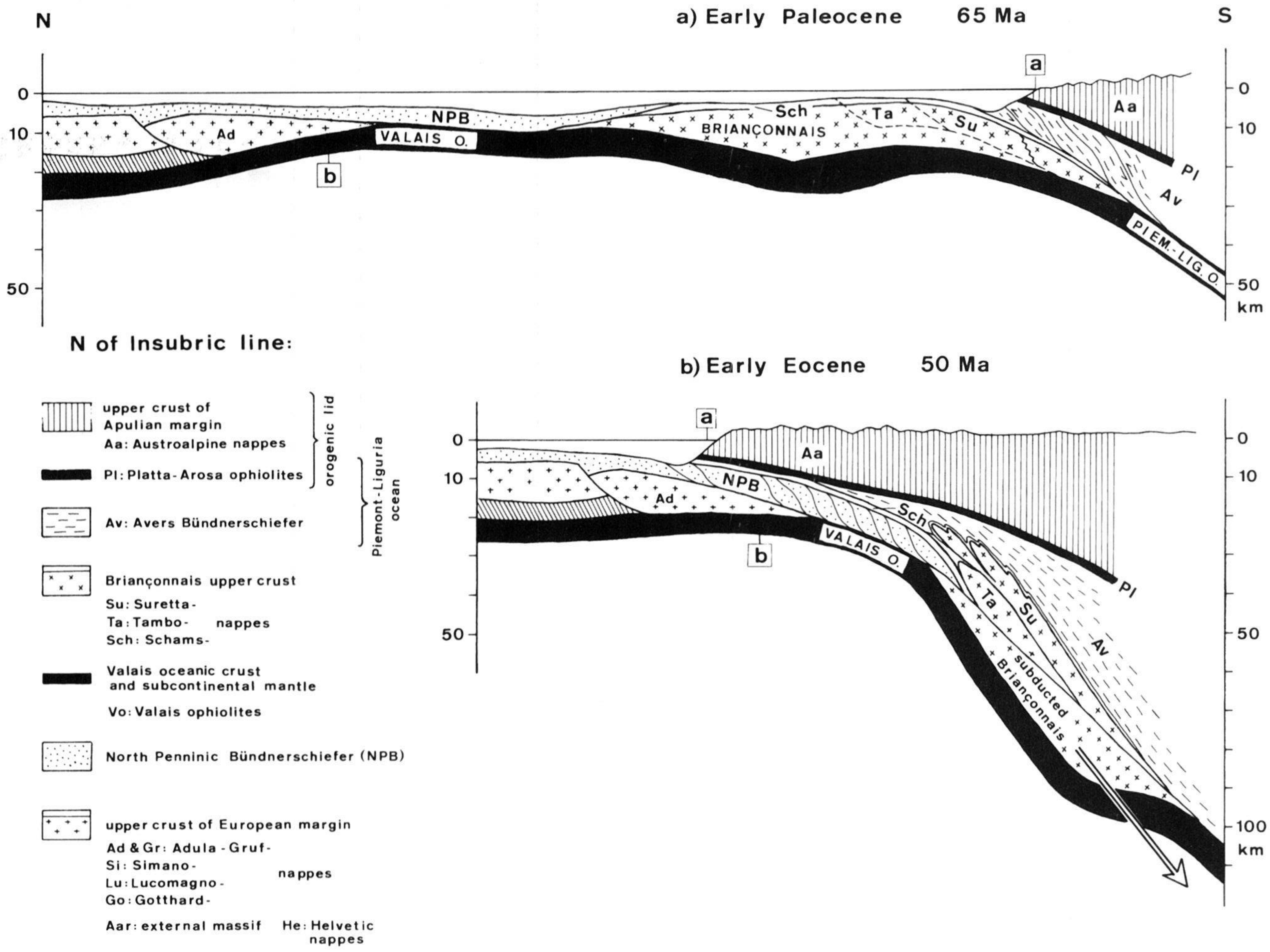
Figure 5c sketches the Adula nappe at its position during peak pressure conditions, as determined by Heinrich (1986) for the northernmost part near Vals (11.5 kb) and for the southernmost part at Alpi Arami in the Cima Lunga subunit (27 kb), respectively. Peak pressures systematically decrease from south to north in the Adula nappe, which is compatible with S-directed subduction. Eclogite facies relics are restricted to a few mafic boudins predominantly found in the highest structural levels of the nappe. The pressure peak was preceded by a first deformation phase (D1) leading to the imbrication of thin slices of continental basement, mafics of unknown age, Triassic rocks (Löw 1987), and basal parts of the Valais Bündnerschiefer (Partzsch et al. 1994, see also Trommsdorf 1993). Therefore an Alpine age of the eclogite-facies metamorphism is undisputable. The formation of the dominant penetrative foliation of the Adula nappe (D2) started under eclogite- and continued under amphibolite facies conditions (Partzsch et al. 1994). Outside the eclogite boudins, this foliation carries a N-S oriented stretching lineation and can be continuously traced from the Adula nappe into the overlying Valais Bündnerschiefer which also contain eclogite facies boudins in their basal part. This points to a common tectonometamorphic evolution of both Adula nappe and Valais Bündnerschiefer, at least during the decompression stage (Partzsch et al. 1994). Given the fact that sedimentation in the Bündnerschiefer basin continued into the Eocene, a Tertiary age of the eclogite-facies metamorphism becomes at least very likely.

4.2 Tertiary orogeny in the Eastern and Western Alps

The large amount of Tertiary N-S-convergence deduced for the Graubünden cross-section has consequences also for the Eastern and Western Alps. Although still far from being properly understood, these will be briefly discussed in the following.

For the Eastern Alps, we depart from the classical view that the Tauern window was closed in the Cretaceous (e.g. Frisch 1976) on structural and paleogeographical grounds. Assuming an amount of Tertiary N-S convergence in the Eastern Alps comparable to that of the Graubünden area, we have to place the front of the Northern Calcareous Alps far south of the Tauern window at the start of Tertiary orogeny. Structural work of Kurz et al. (1995) supports this assumption. According to these authors, the imbrication of Penninic units within the Tauern window (Venediger nappe and Glockner nappe) was N- to NNE-directed. In contrast, the Cretaceous-age thrusting within the overlying Austroalpine nappes was west-directed (e.g. Ratschbacher et al. 1989). This sequence is the same as that observed at the western end of the Austroalpine in Graubünden (W-directed thrusting in the Trupchun phase, N- to NNE-directed thrusting in the Blaisun phase; see above). In Graubünden, the N- to NNE-directed thrusting which emplaced the Cretaceous nappe stack on the deeper Penninic units, is dated as Tertiary because Paleogene fossils were found in the footwall (e.g. in the Engadine window, Rudolph 1982). Consequently we assume that the Tauern window was closed in the Early Tertiary, when the Austroalpine units, together with Piemont-Ligurian ophiolites at their base, were transported northward as one large thrust mass. During this northward transport, the Glockner nappe (probably of Valais origin, as discussed earlier) and the Venediger nappe (distal "Helvetic" European margin according to Lammerer 1986, 1988) were accreted to the orogenic wedge. Differently from the Central Alps, Tertiary N-S convergence in the Eastern Alps was partly compensated by eastward escape (or "extrusion", Ratschbacher et al. 1991). This process started already during the Paleogene (see Eisbacher & Brandner, this volume, for a Tertiary-aged overprint related to sinistral strike-slip motions in the NCA).

Whereas the tectonics of the Central and Eastern Alps may be reconciled in the way


a) Early Paleocene 65 Ma
N
S
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BRIANÇONNAIS
NPB
VALAIS O.
Ad
b) Early Eocene 50 Ma
0
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Aa
Pl
Av
NPB
Ad
Sch
Ta
Su
subducted Briançonnais
VALAIS O.
N of Insubric line:
upper crust of Apulian margin
Aa: Austroalpine nappes
Pl: Platta-Arosa ophiolites
orogenic lid
Piemont-Liguria ocean
Av: Avers Bündnerschiefer
Briançonnais upper crust
Su: Suretta-
Ta: Tambo- nappes
Sch: Schams-
Valais oceanic crust and subcontinental mantle
Vo: Valais ophiolites
North Penninic Bündnerschiefer (NPB)
upper crust of European margin
Ad & Gr: Adula-Gruf-
Si: Simano-
Lu: Lucomagno- nappes
Go: Gotthard-
Aar: external massif
He: Helvetic nappes

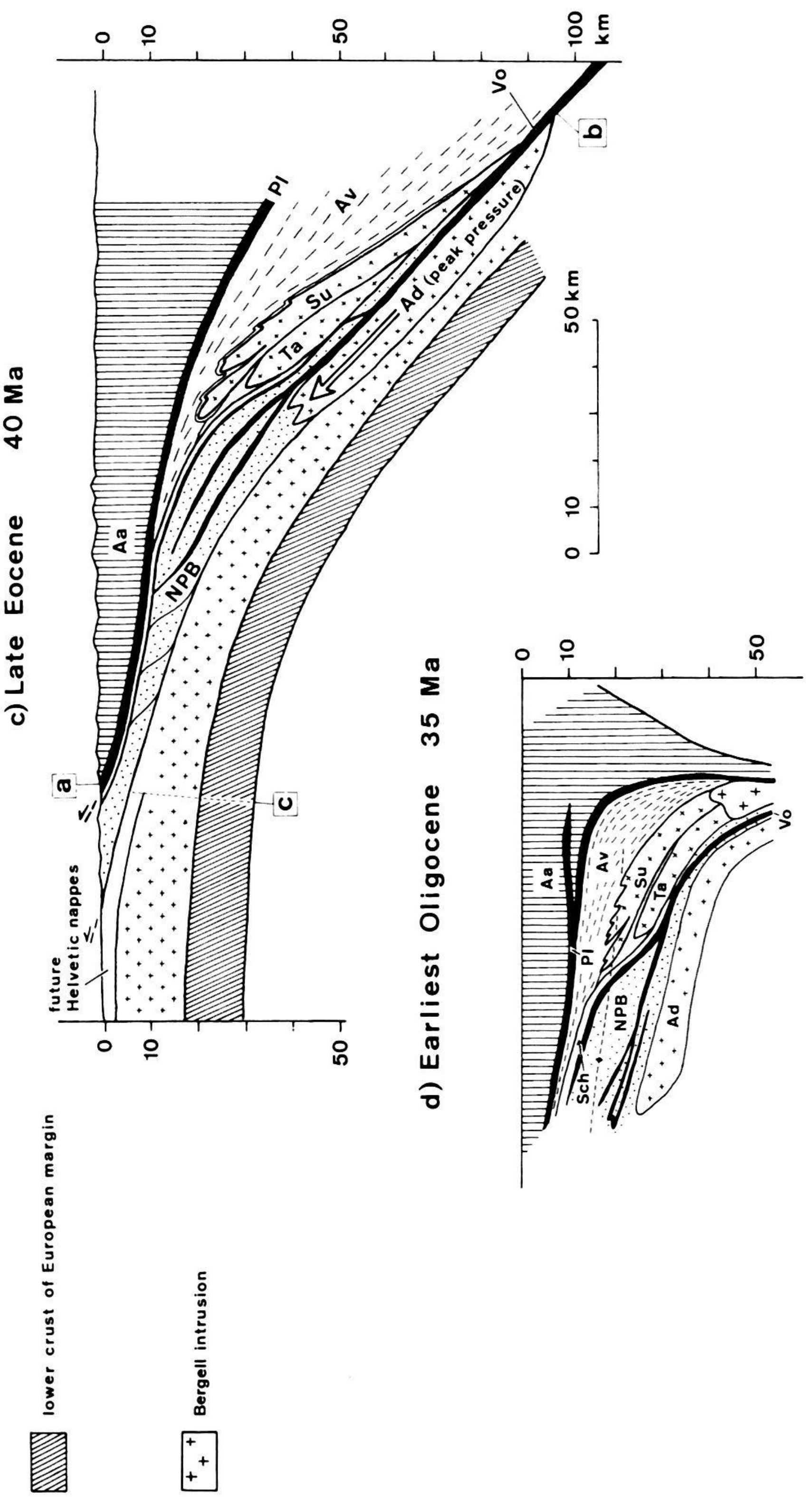

Fig. 5. Reconstructed and area-balanced north-south profiles for the eastern Central Alps in Tertiary time, showing successive incorporation of Briançonnais, Valais and distal European margin units into the orogenic wedge. See Plate 1 for location of profile. After Schmid et al., in press b.

proposed above, the deduced 500 km of Tertiary N-S shortening between Apulia and the European foreland result in a major problem regarding the tectonic evolution of the Western Alps. In this area, the main shortening direction during the Tertiary was apparently E-W (Platt et al. 1989). An earlier phase of north- to northwest-directed movement, however, is documented by stretching lineations in eclogite-facies rocks (Choukroune et al. 1986). Choukroune et al. attributed this northward shearing to the Cretaceous orogeny – probably because, at that time, a Cretaceous age was generally assumed for eclogite-facies metamorphism in the Alps. Monié & Philippot (1989), on the other hand, determined an Eocene age for the high-pressure event in eclogites of the Monte Viso area, bearing a north-south stretching lineation. Consequently, it is at least possible that the high-pressure event in the Western Alps was related to Early Tertiary south-directed subduction, as in the Central Alps of Switzerland. The westward thrusting in the Western Alps would then be younger, starting at about 40 Ma (Choukroune et al. 1986).

To explain this westward thrusting, large amounts of strike-slip faulting and independent motion of blocks such as the Adriatic or South-Alpine block south of the Insubric line are inevitable, as pointed out by Laubscher (1991). Much of the E-W-shortening may be due to an independent W-ward motion of the Adriatic block during the Tertiary, decoupled from the Central Alps by dextral movements along the Insubric line and its precursors. Although such dextral decoupling may explain the E-W shortening, a substantial northward translation of the Adriatic block relative to the western foreland of the Alps is also necessary. This means that the Western Alps probably acted as a N-S-striking, sinistrally transpressive belt, as proposed by Ricou & Siddans (1986). As an alternative explanation, Platt et al. (1989) assume a general west-northwest directed plate movement vector of Adria, deflected into north- and west-directed components of tectonic transport during the Tertiary (in the Western and Central Alps, respectively) due to gravitational forces. We doubt that this model can explain the very substantial amount of N-S shortening deduced for the eastern part of the Central Alps.

5. Timing of eclogite facies metamorphism: radiometric data

During the Alpine orogeny, eclogites formed in rocks originating from all paleogeographic domains of the Alps: the Apulian continental crust (Austroalpine nappes), the Piemont-Liguria ocean, the Briançonnais s.l., the Valais ocean and the distal European margin (Pl. 1). In the continental units, pre-Alpine eclogites also exist but these are not discussed here. Alpine, coesite-bearing ultra-high-pressure rocks have been reported so far from units of the Briançonnais s.l. (Dora Maira) and from Piemont-Ligurian ophiolites (Zermatt-Saas). Comprehensive reviews of eclogite-facies rocks in the Alps are provided by Droop et al. (1990) and Dal Piaz et al. (1993).

Information on radiometric ages concerning Alpine eclogite facies metamorphism for some selected areas and localities is presented in Plate 1 and will be discussed below. Whenever possible, data obtained from high-retentivity systems (U-Pb, Sm-Nd) were preferred over ^{39}Ar-^{40}Ar or K-Ar ages from phengites. As recently discussed by von Blanckenburg & Davies (1995, p. 126), the latter group of age data is often affected by excess argon and is yielding much too high age values. An increasing number of studies favours the presence of excess argon in phengites from the Dora Maira massif (Arnaud & Kelley in press; Hammerschmidt et al. 1995) and the Sesia Zone (Ruffet et al. 1995).

5.1 *Austroalpine units*

The Cretaceous age of Alpine eclogites in the Austroalpine units is well established. These eclogites are found in basement rocks of the Central Austroalpine complex (between the NCA and the Insubric line). In the Koralpe area, eclogite was formed from a Permian gabbro protolith, as shown by Thöni & Jagoutz (1992, 1993) who determined Permian ages in a metagabbro relic that escaped eclogitization. Therefore, the eclogite is Alpine. The same authors bracketed the age of the high-pressure metamorphism between 150 and 100-90 Ma, using Sm-Nd, Rb-Sr and Pb-Pb determinations (Thöni & Jagoutz 1993).

5.2 *Sesia nappe*

The Sesia nappe is the largest eclogite-facies terrane in the Alps. Pressures and temperatures during the eclogite stage reached 14–16 kb and 550 °C (Lardeaux & Spalla 1991). Until recently, an Early Cretaceous age for the eclogite metamorphism was generally assumed, based on a Rb-Sr whole-rock isochron and Rb-Sr and K-Ar mineral ages (Oberhänsli et al. 1985). Recently, Ramsbotham et al. (1994) determined Rb-Sr phengite ages between 46 ± 2 Ma and 63.3 ± 0.5 Ma, and an U-Pb age of sphene at 66.4 ± 0.4 Ma in the internal part of the Sesia zone in the Orco valley. These authors interpret the 66 Ma age as related to the high-pressue event. The latter interpretation is supported by recently determined U-Pb SHRIMP ages of zircon (about 65 Ma; D. Gebauer, personal communication). Peak pressures may have been reached somewhat earlier, that is, in the Late Cretaceous, but an Early Cretaceous age for the eclogite facies event appears unlikely in the light of these new data.

5.3 *Piemont-Ligurian zone*

In the Western Alps, units with Piemont-Ligurian ophiolites and associated calcschists (schistes lustrés) can be subdivided in two groups, a structurally lower one (Zermatt-Saas zone) that suffered eclogite-facies metamorphism (Bearth 1959, 1967), and a higher one (Combin zone) with only blueschist facies (Kienast 1973). Coesite inclusions in garnet found in the Valtournanche area of the Zermatt-Saas zone even indicate ultra-high-pressure metamorphism (26 to 28 kbar, 590–630 °C, Reinecke 1991). Like in the Sesia nappe, a Cretaceous age of the high-P metamorphism was generally assumed, but recently Bowtell et al. (1994) determined a latest Cretaceous to Early Tertiary age (52 ± 18 Ma; Sm-Nd garnet-omphacite whole-rock isochron) for the Pfulwe locality near Zermatt. In addition, concordant phengite ^{39}Ar-^{40}Ar plateau ages of 48–51 Ma from eclogitic metagabbros in the Monte Viso ophiolitic massif document a mid-Eocene age of the high-pressure metamorphism there (Monié & Philippot 1989).

5.4 *Briançonnais s.str. and "internal massifs"*

In the western Alps, the Briançonnais s.str. was affected only by blueschist-facies metamorphism. This event is clearly of Tertiary age, because the metamorphosed sediments reach into the Paleocene to Eocene (Ellenberger 1958, Michard 1977). The so-called internal massifs (Dora Maira, Gran Paradiso, Monte Rosa), interpreted by most authors to represent the former passive margin between the Briançonnais s.str. and the Piemont-Ligurian ocean, bear eclogites and, in the Dora Maira massif, even pyrope quartzite with coesite, indicating maximum pressure of about 30 kbar (Chopin 1984, Chopin et al. 1991, Schertl et al. 1991). Conflicting ages exist for the ultra-high-P event: U-Pb and Rb-Sr (Paquette et al. 1989) as well as Ar-Ar dating (Monié and Chopin 1991) yielded Cretaceous ages (120–90 Ma), while Sm-Nd and U-Pb work of Tilton et al. (1991) yielded an age of 38 Ma. The Tertiary age is supported by U-Pb SHRIMP work on zircon (Gebauer et al. 1993).

5.5 Valais and distal European margin

The paleogeographically most external occurrences of Alpine eclogite are in Valais units and in units from the distal part of the European margin: in the Roignais-Versoyen unit (Schürch 1987), in the Adula nappe and in the Eclogite Zone of the Tauern window. An Eocene age (35–44 Ma) was recently established for the high-pressure metamorphism in the Cima Lunga unit of the Adula nappe (850–900 °C and 35–42 kbar according to Becker 1993), based on Sm-Nd garnet-clinopyroxene-whole rock isochrons (Becker 1993) and U-Pb SHRIMP data on zircon (Gebauer 1994); for details see Plate 1. The high-pressure metamorphism in the middle Adula nappe reached temperatures of 600–650 °C at minimum pressures of 20–23 kbar (Meyre et al. 1995). The age of this metamorphism is not yet dated unequivocally, but the large majority of available radiometric data also point to an Eocene age. The Eclogite zone in the southern part of the central Tauern window is a metasedimentary series of Mesozoic age with intercalated eclogite lenses, located at the base of the Glockner nappe, directly overlying the Venediger nappe (Frank et al. 1987). Peak metamorphic conditions were ca. 600 °C at 20 kbar, followed by a blueschist to eclogite facies stage at $T < 450$ °C and $P > 10$ kbar, followed by a greenschist facies overprint during exhumation at 525 °C/5–6 kbar (Zimmermann et al. 1994). Phengite ^{39}Ar-^{40}Ar ages ranging between 32 and 36 Ma were attributed to the blueschist to eclogite facies event mentioned above (Zimmermann et al. 1994).

In conclusion, there is an increasing body of radiometric evidence indicating that high-pressure metamorphism in the Alps occurred in the Cretaceous as well as in the Tertiary period. Whereas the Cretaceous age of eclogites in the Austroalpine units is well-established, an Early Tertiary age appears more likely for eclogites and ultra-high-pressure rocks in the Central and Western Alps, with the exception of the Sesia zone which reached peak pressures probably in the Late Cretaceous.

6. Discussion

In order to discuss the timing of eclogite formation in the framework of paleogeography, we make the assumption that eclogites and ultra-high-pressure rocks formed either within a subducting slab of oceanic lithosphere or in the lower plate during continental collision. These may not be the only ways to produce high pressure rocks, but without any doubt the simplest. Such an assumption poses a serious constraint on possible models of the tectonometamorphic evolution of the Alps.

Following Neubauer (1994), we assume that Cretaceous eclogite metamorphism in the Central Austroalpine units occurred after the Late Jurassic closure (Kozur 1991) of the Meliata-Hallstatt ocean, when the continental crust from the opposing, southeastern margin of this ocean was thrust westward or northwestward over the Austroalpine (Fig. 4a, b). Parts of the suture and even sedimentary rocks from the opposing margin are preserved in the eastern part of the Northern Calcareous Alps (Kozur & Mostler 1992). In the footwall of the suture, a W- to NW-directed thrust belt formed and propagated westward. The thrust front reached the formerly passive margin between the Austroalpine and the Piemont-Liguria ocean in Graubünden after 90 Ma. In our opinion, the upper plate which was carried over the Austroalpine crust is not represented by the Southern Alps, as proposed by Channell et al. (1992), but has to be looked for in the Pannonian area, that is, to the east of the Austroalpine realm. The Tisia microplate of Kovacs (1982) is a good candidate. The Cretaceous eclogites were overprinted by Barrowian-type metamorphism and exhumed already in the Late Cretaceous. For example, the Saualpe-Koralpe eclogites cooled through 300° at 70 ± 10 Ma (Thöni & Jagoutz 1993). We explain this exhumation with Late Cretaceous extension: The upper plate of the collision couple slid back to the east, as indicated by the ubiquitous Late Cretaceous east-directed low-angle extensional faults in the Central Austroalpine (Krohe 1987, Ratschbacher et al. 1989, Froitzheim et al. 1994, Neubauer et al. 1995a). This explains why almost no remnants of the upper plate are found today in the Eastern Alps.

Subduction of the Piemont-Ligurian oceanic lithosphere started in the Late Cretaceous, as evidenced by the sedimentary record in Liguria. There, the oldest preserved ophiolite detritus shed from an accretionary wedge (Ruga del Bracco) is dated as Campanian (Elter 1993). We assume that the subduction zone dipped under the Apulian margin. The Sesia unit was part of an extensional allochthon near the Apulian margin and was therefore the first continental unit to be subducted. It reached a depth of around 45 km probably during the Late Cretaceous (Ramsbotham et al. 1994). An Early Cretaceous age of the high-pressure metamorphism in the Sesia nappe (Oberhänsli et al. 1985) is possible, but would require a "stealthy" subduction that left no imprint in the sedimentary record of adjacent paleogeographic domains.

Following the subduction of Sesia, the remaining part of the Piemont-Ligurian lithosphere was subducted. At some time during the latest Cretaceous or Early Tertiary, the direction of shortening changed from east-west to north-south in the Central and Eastern Alps. Subduction of Zermatt-zone ophiolites must have started in the Late Cretaceous to allow the time necessary for these rocks to reach depths of up to 100 km (Reinecke 1991) by Early Tertiary time (Bowtell et al. 1994). In the Early Tertiary, the internal margin of the Briançonnais terrane entered the subduction zone. Parts of the upper crust were sheared off and transported toward the external zones, like the Préalpes nappes. Large quantities of Briançonnais (s.l.) crust must have been subducted (Schmid et al. in press b). If we assume, as do most authors, that the "internal massifs" represent the former margin between the Briançonnais and the Piemont-Liguria ocean, the high- and ultra-high-pressure metamorphism in the "internal massifs" cannot be Cretaceous, because the pelagic sedimentation in this domain reached into the Paleocene (Breccia nappe, Chessex 1959).

Along the transect through Eastern Switzerland the Briançonnais was progressively incorporated into the orogenic wedge during the Paleocene to Early Eocene. The Valais oceanic lithosphere was subducted during the Early Eocene, while the distal margin of the European plate (Adula nappe) did probably not enter the subduction zone before the end of the Early Eocene. An earlier subduction of the Adula unit is not possible since the sedimentation of flysch in the more internal Valais basin lasted into the Early Eocene (Nänny 1948, Ziegler 1956, Eiermann 1988). By the Late Eocene (40 Ma), the Adula nappe was subducted to the depth corresponding to peak pressure conditions. We assume a similar timing for the eclogite zone of the Tauern window.

Conclusions

The paleogeographic reconstruction of the Alps based on the sedimentary record and the timing of high- and ultra-high pressure metamorphism in basement and cover units are two intimately related aspects of the same problem. At present, any attempt to reconcile the two can only be preliminary and incorrect in many details. Nevertheless, we think that the following working hypothesis is reasonable:

(1) The Alpine orogeny is controlled by subduction and collision processes along three partly oceanic basins, from internal to external: Meliata-Hallstatt (opened in the Middle Triassic, closed in the Late Jurassic), Piemont-Liguria (opened in the Middle Jurassic, closed in the Paleocene to Early Eocene), and Valais (opened in the Late Jurassic to Early Cretaceous, closed in the Late Eocene).

(2) Eclogite-facies metamorphism is related to the closure of these oceans and related subduction processes. It occurred within downgoing oceanic slabs during subduction or within lower continental plates during continent collision. Since the timing of subduction and closure of the three oceanic basins is strongly different, eclogite formation must also be of different age in the different paleogeographic domains of the Alps.

(3) Two orogenic cycles can be distinguished. Cretaceous orogeny encompasses the formation of a westward-directed thrust belt in the Austroalpine units after continent collision along the Meliata-Hallstatt ocean and the subduction of Piemont-Ligurian oceanic lithosphere together with parts of the Margna-Sesia continental fragment. Eclogite metamorphism in these units is therefore Cretaceous (to Early Tertiary in the case of the Piemont-Ligurian units).

(4) Tertiary orogeny was dominated by north-south convergence in the Central and Eastern Alps. E-W-shortening predominates in the Western Alps, possibly due to the independent motion of the Adria or South Alpine block and/or sinistral transpression parallel to the N-S trending chain of the Western Alps. In the Central and Eastern Alps, the N-S shortening can be characterized as the formation of an orogenic wedge through progressive incorporation, from south towards north, of the Briançonnais, Valais and distal European margin units. A Tertiary age is assumed for high-pressure metamorphism in these paleogeographic units.

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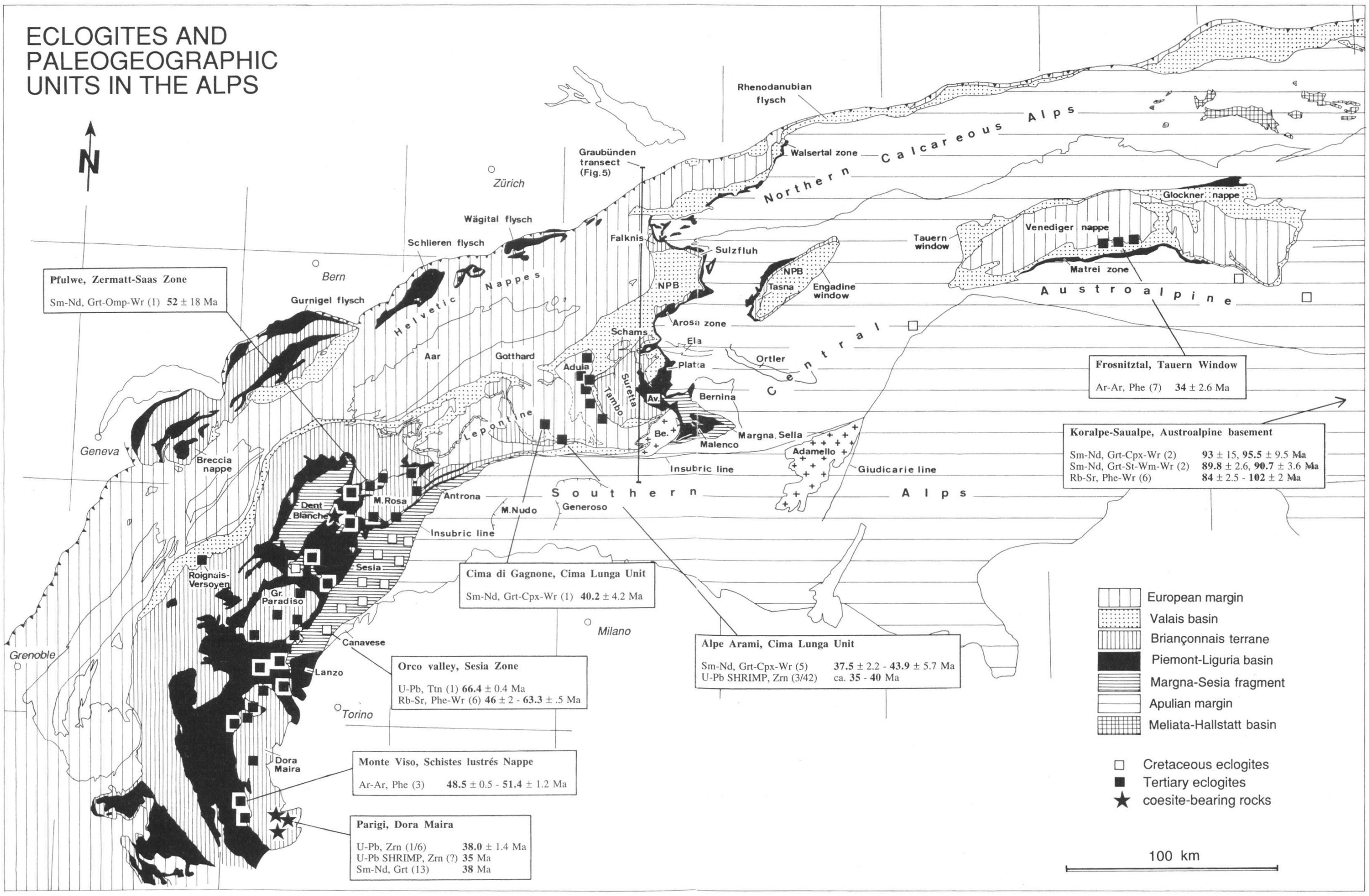

Plate 1. Paleogeographic map of the Alps, also showing occurrence and presumed ages of Alpine eclogite and ultra-high-pressure rocks. Av., Avers Bündnerschiefer; Be., Bergell intrusion; NPB, North Penninic (Valais) Bündnerschiefer. The sources for radiometric age data are given in the text. For each radiometric system, the number of age determinations is indicated in brackets. Mineral abbreviations used: Cpx Clinopyroxene, Grt Garnet, Omp Omphacite, Phe Phengite, St Staurolite, Ttn Titanite, Wm White mica, Wr Whole rock, Zrn Zircon.