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Feasibility of Double Slab Breakoff (Cretaceous and Tertiary) during the Alpine Convergence

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Key words: Slab Breakoff, magmatism, metamorphism, subduction, orogenesis, Austroalpine, Penninics

ABSTRACT

It has been proposed in newer models of the Alpine convergence that closure of oceanic basins and following continental collision was separated into two discrete events: Eoalpine (Cretaceous) closure of a presumed westward extension of a South-Tethys ocean (Vardar-Meliata-Hallstatt), followed by Mesoalpine (Tertiary) closure of the Penninic basins (Piemont, Valais). Further, according to the slab breakoff model, closure of an oceanic basin and partial subduction of continental lithosphere can lead to detachment and falling away of the oceanic lithosphere. Therefore the geological imprints of slab breakoff could be found twice in the Alps.

In this paper we test the feasibility of this hypothesis by compiling literature data relevant to the surface expressions predicted from the slab breakoff model. a) Ages from high-pressure continental rocks fall into two groups (after taking into account the likely effect of excess argon in phengites): 110–95 in Austroalpine units, 50–30 Ma in Penninic units. b) Greenschist facies metamorphism affected parts of the Austroalpine from 100 to 85 Ma, Penninic units from 40–30 Ma. c) High-temperature regional metamorphism peaked at ca. 90 Ma in the Austroalpine, at ca. 29 Ma in the Penninics. d) Most importantly, some minor basaltic magmatism occurred at 100 Ma in the Austroapline, more pronounced bimodal magmatism is prominent along the Periadriatic Lineament from 43 to 25 Ma. e) Rapid erosion is witnessed by basins formed from 90 to 60 Ma in the Austroalpine (Gosau), Molasse and Po-Basin from 35 to 10 Ma. f) East-west directed extensional exhumation is documented by low-angle normal faulting at 90–70 Ma in the Austroalpine and from 30–10 Ma along the Tauern Window and Central Alps, respectively.

All these features are predicted by the slab breakoff model. The broad similarities and good separation in time between both orogenic cycles may suggest that they were affected by the same process in different periods. However, none of the above expressions is exclusive to slab breakoff, nor is the timing in every case well-constrained. Therefore, rather than using these observables as definite proof of the double-slab breakoff hypothesis, the aim of this paper is to demonstrate how these criteria can be used to constrain the model. This should allow its confirmation or rejection in the future.

ZUSAMMENFASSUNG

In neueren Modellen der Alpenkollision ist vorgeschlagen worden, dass zwei getrennte Orogenesen als Folge der finalen Subduktion ozeanischer Becken stattgefunden haben: ein südliches Becken (Vardar-Meliata-Hallstatt Ozean) wurde in der Kreide und ein nördliches (Penninikum) im Tertiär geschlossen. Dies hatte die eoalpine Orogenese im Ostalpin und die mesoalpine im Penninikum zur Folge. Ausserdem wurde kürzlich ein generelles Modell zur Abtrennung und zum Absinken subduzierter ozeanischer Lithosphäre («Slab Breakoff») publiziert. Dieser Prozess tritt dann auf, wenn sich ozeanische Becken geschlossen haben und kontinentale Lithosphäre teilweise subduziert wird. Slab Breakoff müsste demnach zweimal in den Alpen stattgefunden haben.

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In dieser Arbeit evaluieren wir, ob Slab Breakoff die vorausgesagten Folgen gehabt hat: a) Alter von Hochdruckgesteinen verteilen sich auf zwei verschiedene Gruppen: 110–95 Ma im Ostalpin, 50–30 Ma im Penninikum (vermutlich Exzess-Argon-haltige Phengitalter wurden dabei nicht berücksichtigt). b) Grünschieferfaziesmetamorphose in Teilen des Ostalpins von 100 bis 85 Ma, im Penninikum von 40–30 Ma. c) Hochtemperierte Regionalmetamorphose hatte ihren Höhepunkt vor ca. 90 Ma im Ostalpin, vor ca. 29 Ma im Penninikum. d) Vereinzelter basaltischer Magmatismus trat vor 100 Ma im Ostaplin auf, der wohlbekannte tertiäre Magmatismus fand von 43 bis 25 Ma an der Periadriatischen Linie statt. e) Schnelle Hebung und Erosion wird belegt durch intramontane Becken, die sich von 90 bis 60 Ma im Ostalpin bildeten (Gosau), Molasse und Po-Becken waren von 35 bis 10 Ma Absatzgebiete für Sedimente. f) Ost-West gerichtete Extension an Normalabschiebungen geschah vor 90–70 Ma im Ostalpin, von 30–10 Ma entlang des Penninischen Tauernfensters und der Zentralalpen.

Alle diese Effekte werden im Prinzip durch das Slab Breakoff Modell vorausgesagt. Allerdings können sie auch durch diverse andere Prozesse hervorgerufen werden. Zudem ist ihre zeitliche Abfolge nicht immer gut belegt. Beide Orogenesen scheinen jedoch sehr ähnlich verlaufen zu sein und könnten daher auf denselben Prozess zurückzuführen sein. Wir behaupten nicht, dass dies definitiv Slab Breakoff gewesen sein muss, aber wir wollen hier Bewertungsmassstäbe vorschlagen, mit denen diese Hypothese getestet werden kann.

1. Introduction

In the current debate on the evolution of the Alps, two models have emerged recently that were developed with the particular purpose of explaining some of the most controversial aspects of Alpine tectonics. These are:

1) The concept that the Alpine convergence comprised two distinct orogenic events, one Cretaceous ("Eoalpine") and the other Tertiary ("Mesoalpine") in age, rather than a continuous orogenic evolution (Hoinkes et al. 1991, Thöni & Jagoutz 1993, Froitzheim et al. 1994, 1995; Schmid et al. 1996). This concept reconciles the apparently secularly distinct structural evolution in the Cretaceous and Tertiary, respectively, of the Austroalpine / Penninic boundary, and the fact that isotopic ages of high-pressure minerals seem to give ages of 110–95 Ma for Austroalpine eclogite facies rocks and 50–30 Ma for Penninic high-P rocks. It is postulated that the Eoalpine metamorphic events resulted from subduction of a western continuation of the Vardar-Hallstatt-Meliata ocean and following continental collision within the Austroalpine units. The Mesoalpine events, in contrast, are due to the closure of the Penninic Piemont and Valais basins.

2) The model of "Slab Breakoff" has been used to explain syncollisional magmatism preceded by subduction of continental lithosphere to mantle depths (Davies & von Blanckenburg 1995, von Blanckenburg & Davies 1995). In this model, continental lithosphere follows oceanic lithosphere into the subduction zone after the closure of oceanic basins until the buoyancy thus created leads to breakoff and falling away of the subducted oceanic slab. Asthenospheric mantle will rise into the gap and conductively heat the overriding lithosphere. Partial melting of the lithospheric mantle will generate small amounts of syncollisional basaltic volcanism. The rising melts and heat can induce crustal melting leading to granitic intrusions. The model has been used to explain the generation of the Tertiary Periadriatic plutons (von Blanckenburg & Davies 1995). Breakoff will also facilitate the rise and exhumation of high-pressure continental sheets, thermal metamorphism, extensional and erosional collapse and deposition of the erosional products in intramontane basins. Tomographic images of the structure below the Alps have shown evidence for detached bodies with elevated P-wave velocities (DeJonge et al. 1994). These have been interpreted as the detached Piemont and Valais oceanic lithosphere, re-

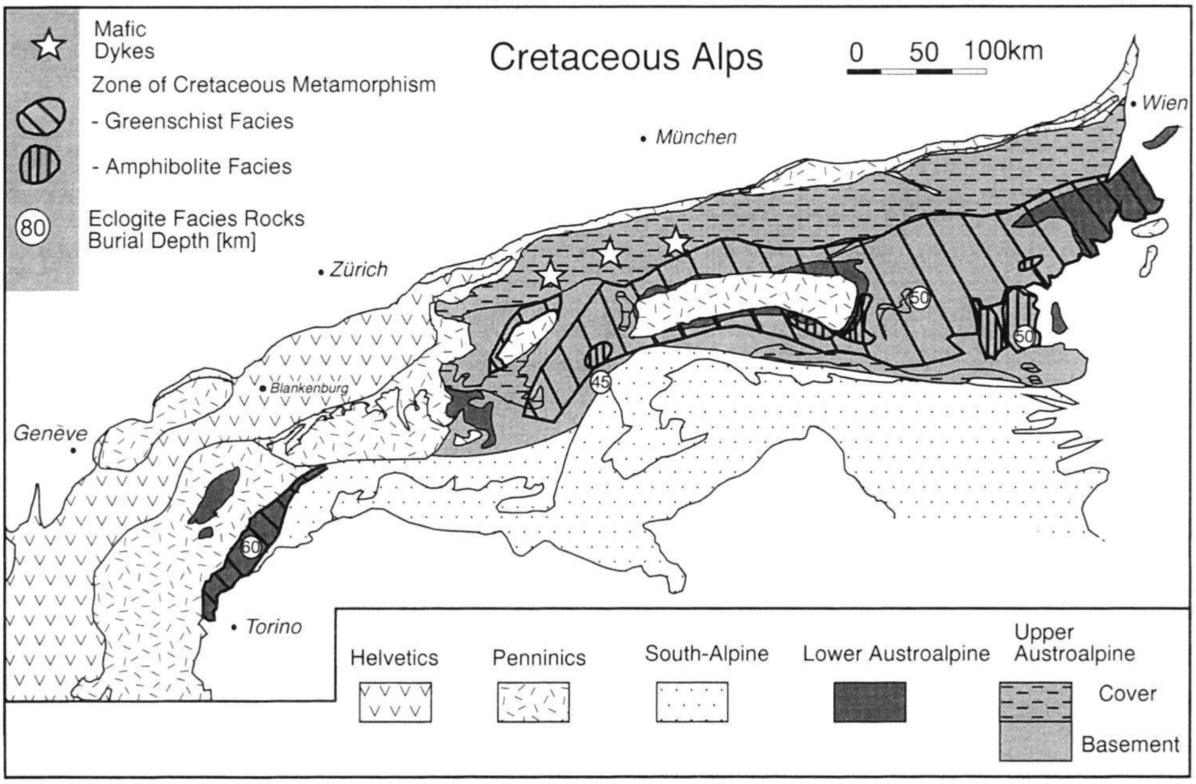


Fig. 1. Tectonic map of the Alps showing Cretaceous features that could be the result of slab breakoff. Location of mafic dykes is after Trommsdorff et al. (1990); areas of Cretaceous thermal metamorphism is as compiled by Martinotti & Hunziker (1984) and Hoke (1990); eclogite facies rocks are after Oberhänsli et al. (1985), Miller (1990), Hoinkes et al. (1991) and Thöni & Jagoutz (1993).

spectively (Marchant & Stampfli 1995). Removal of the Alpine lithospheric root during the mid-Tertiary has also been invoked by Dal Piaz & Gosso (1994) to explain Mesoalpine metamorphism, magmatism and extensional deformation.

In this paper we will provide criteria to test whether the process of slab breakoff may have acted in the Cretaceous as it has been postulated for the Tertiary. If slab breakoff is a common feature following closure of oceanic basins, then this process may have also acted after the closure of the postulated south-Tethys ocean in a manner similar to that of the Penninic closure. The tests we will use are 1) Magmatism; 2) High-P metamorphism; 3) Thermal metamorphism; 4) Orogen deformation; 5) Erosional Products. We will not discuss tomographic evidence, as this has been attempted elsewhere (Marchant & Stampfli 1995). It is not the aim of this paper to claim that this process was a definite feature of the Eoalpine evolution. Rather, we would like to show in which manner geological observables can be used to constrain or reject the model and focus research to come towards filling some of the most obvious gaps in understanding.

2. Geological Evidence for Slab Breakoff

In this section we compare the Cretaceous with the Tertiary surface expression, respectively, of a potential slab breakoff process. The predictions themselves have been

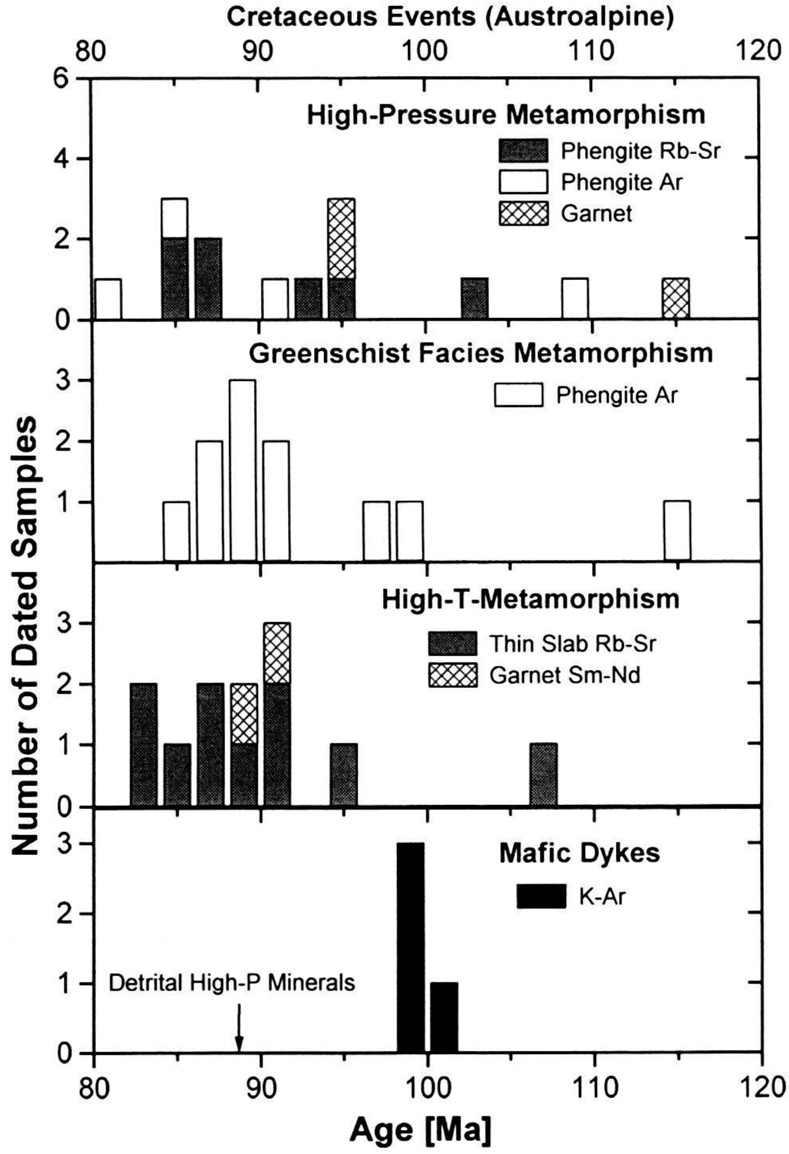


Fig. 2. Compilation of ages from metamorphic and magmatic events in the Austroalpine. For the greenschist and high-T metamorphism only chronometers that would yield growth ages at the respective conditions have been compiled (<600°C for garnet Sm-Nd and Rd-Sr, <550°C for phengite Rb-Sr and <400°C for phengite K-Ar). Data sources are: High-P metamorphism: Hunziker (1974), Oberhänsli et al. (1985), Thöni & Jagoutz (1992). Greenschist facies: Thöni (1980, 1983, 1986). High-T metamorphism: Thöni (1983, 1986), Thöni & Jagoutz (1992). Mafic dykes are from Trommsdorff et al. (1990). The deposition age of detrital high-pressure minerals is from Winkler & Bernoulli (1986).

discussed at length in the literature (Davies & von Blanckenburg 1995, Yoshioka & Wortel 1995) and will not be repeated here in great detail. Also the Tertiary features of slab breakoff have been compiled elsewhere (von Blanckenburg & Davies 1995) and will only by summarized briefly in this section.

2.1 Magmatism

Syncollisional basaltic and granitoid magmatism are the most valuable witnesses of slab breakoff. Basalts are thought to be generated by low-degree partial melting of the enriched lithospheric mantle above the breakoff trace. This is where hot asthenospheric mantle is upwelling into the gap of the separating plates. Granitoids can be generated if the amount of basalt rising into the continental crust was large, such that significant crus-

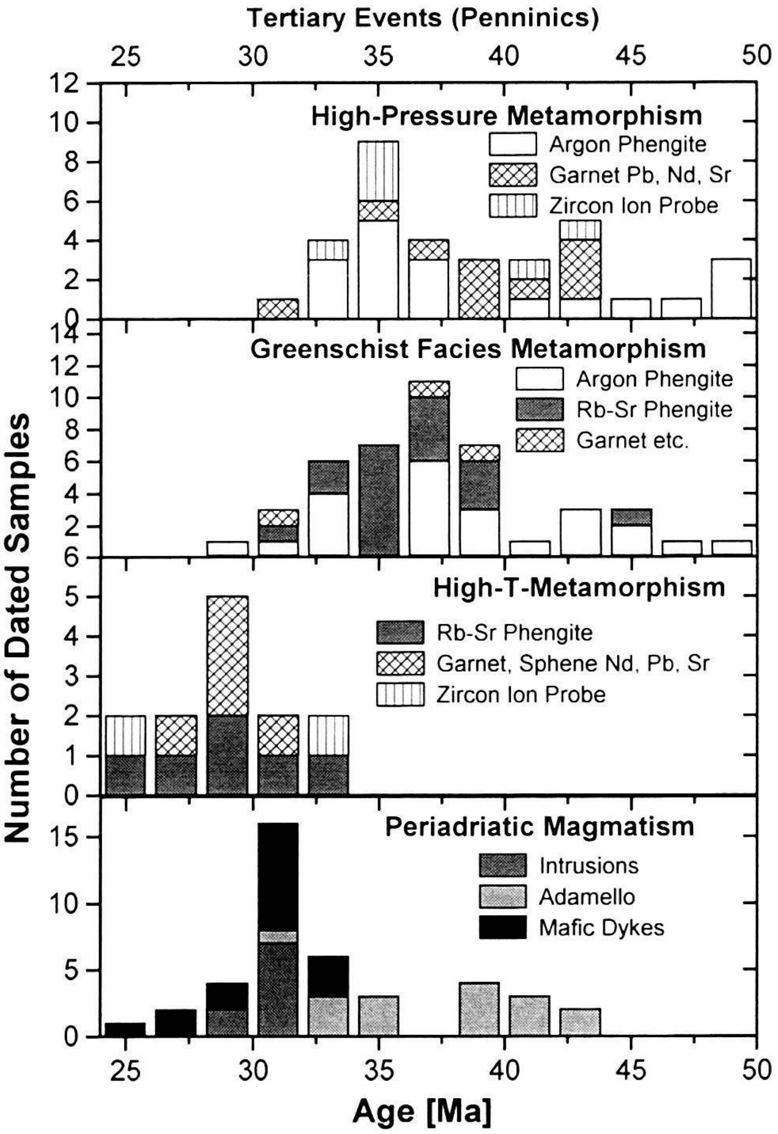


Fig. 3. Compilation of ages from metamorphic and magmatic events in the Penninic nappes. The sources for magmatic ages and high-P ages are essentially those as compiled by von Blanckenburg & Davies (1995). Note, however, that all Cretaceous high-P K-Ar ages have been omitted, as these are likely to contain excess argon (Arnaud & Kelley 1995, Hammerschmidt et al. 1995). Note also that Takeshita et al. (1994) have measured numerous K-Ar ages from blueschist facies phengites of the Piemont zone west of the Dora Maira Massif, all ranging between 60 and 40 Ma, thus confirming the early Tertiary high-P age of the Penninic calc-schists. New zircon ages for the high-P rocks from Gebauer (1995) have been added. In addition, greenschist facies ages have been compiled from: Hunziker (1969), Bocquet et al. (1974), Delaloye & Desmons (1976), Purdy & Jäger (1976), Wagner et al. (1977), Liewig et al. (1981), Chopin & Monié (1984), Monié (1985, 1990), Monié & Chopin (1991). High-T ages have been compiled from: Vance & O'Nions (1992), Christensen et al. (1994), Inger & Cliff (1994). Ages for intracrustal melting, such as the Novate leucogranite, have not been included.

tal melting can occur. Also conduction of heat, but only in conjunction with thermotectonic processes, may lead to mainly lower crustal melting.

Cretaceous. Basanitic lamprophyres ("Ehrwaldites") have been reported at precisely 100 Ma in the Northern Calcareous Alps (Trommsdorff et al. 1990, also Fig. 1 and 2). The ages seem to be reasonably well constrained, due to the excellent reproducibility between different samples, despite the difficulties of dating whole-rocks with K-Ar. The source of these basanites has been identified to be the lithospheric mantle, at a depth of ca. 80 km and temperatures of 1250°C. The isotopic compositions (ε_{Nd} = +4 to +5, $^{87}Sr/^{86}Sr$ = .703 to.704 and ε_{Hf} = +6.5 (Stille et al. 1989), is in line with this suggestion. The rare earth patterns (Fig. 4) show similar enrichment of the light rare earths as the Tertiary basalts, hinting at low melt fractions and the enriched nature of the mantle source. In contrast to the flat heavy rare earths of the Tertiary dykes, thought to result from strong initial depletion of the garnet-bearing mantle source which became enriched later on, the Cretaceous basanites are much steeper. This suggests that their origin is at the base of the mechanical boundary layer, where strongly depleted mantle could not have been preserved over long periods, due to exchange with the underlying convecting asthenosphere. Similar observations have been made on nephelinites from Central Europe (Wilson et al. 1995). All these observations and the absence of granitoids, respectively, indicate a very minor and short-lasting thermal perturbance at great depth. As the ehrwaldites occur in one nappe, the Lechtal Nappe only, Trommsdorff et al. (1990) concluded that the dykes intruded before major compression leading to nappe stacking. But because the dykes intruded into subvertical strata already, some deformation must have occured before or during their emplacement. Trommsdorff et al. (1990) explain this with a brief extensional period. However, it could also have been related to the verticalization associated with convergence following slab breakoff (Davies & von Blanckenburg 1995, von Blanckenburg & Davies 1995).

Tertiary. Tertiary magmatism, both basaltic and granitoid, occurred from 43–25 Ma, with a pronounced peak at 32 Ma, along the Periadriatic Fault (Fig. 3). The linear alignment of the intrusions can be explained by the trace of slab breakoff, when propagating laterally (Yoshioka & Wortel 1994). Later intra-crustal melting, as witnessed mainly the Novate leucogranite, is unlikely to be related to the mantle melting.

Alternative explanations include a minor extensional phase, after and before compression. Trommsdorff et al. (1990) have explained their dykes with a "horst graben system" within an extensional setting. An extensional phase in the Oligocene has also been proposed as explanation for the Periadriatic plutonism (Laubscher 1983). Whole-lithospheric extension can indeed lead to partial melting of the lithosphere (McKenzie & Bickle 1988). However, we consider this as unlikely at least for the Tertiary, as compression existed throughout the time of the intrusions (Rosenberg et al. 1994, 1995). Subduction volcanism can be rejected by paleogeography (i.e. the Tertiary instrusions are emplaced both in the former downgoing and overriding plate), chemistry (the Cretaceous basanites are non-typical for subduction melting (Trommsdorff et al. 1990)) and theory (the subduction velocities of ca. 0.5–1 cm/a were too slow to allow for melting of the wedge corner (Davies & Stevenson 1992, von Blanckenburg & Davies 1995)). Other alternatives are convective removal of a thickened thermal boundary layer or delamination (Bird 1978, Houseman et al. 1981), but these have been considered unlikely in those cases where continental collision has been preceded by subduction of oceanic lithosphere (Davies & von Blanckenburg 1995).

2.2 High-Pressure Metamorphism

When continental lithosphere follows ocean floor into the subduction zone, light crustal layers can delaminate and will move, due to their buoyancy, back into the crust (van den Beukel 1992). Removal and rapid uplift of such slices from mantle depth will be triggered by the heating of the crustal slab during breakoff (von Blanckenburg & Davies 1995). So we would expect peak pressure to be attained up to briefly before breakoff and rapid uplift to occur from briefly before breakoff up to briefly thereafter.

Our interpretation of high-P ages in the Alps is principally based on high-retentivity chronometers, such as garnet Sm-Nd and U-Pb. K-Ar and Ar-Ar dating in continental

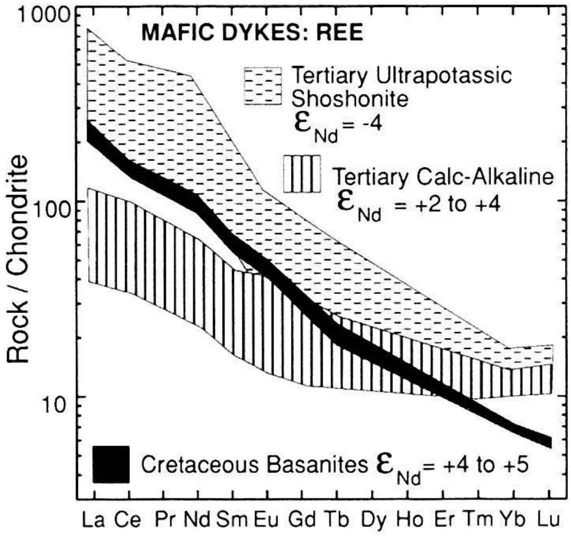


Fig. 4. Rare earth element patterns from Cretaceous and Tertiary mafic dykes in the Alps. The Tertiary dykes are as compiled by von Blanckenburg & Davies (1995), the Cretaceous basanites from the Northern Calcareous Alps are from Trommsdorff et al. (1990).

high-P rocks seems to be fraught with difficulties due to excess argon. This has been reported in particular for the Dora Maira Massif, where Cretaceous phengite Ar-Ar ages seem to be masked by excess argon (Arnaud & Kelley 1995, Hammerschmidt et al. 1995). It seems to be a general problem in high-P rocks (Li et al. 1994). We therefore see no justification for a continuous succession of high-P ages from 120 to 30 Ma, as suggested by numerous authors (e.g. Polino et al. 1990). Rather, we suggest that the high-P event was between 110 and 95 Ma in the Austroalpine (Fig. 2), and 55 to 30 Ma in Penninic units (Fig. 3). We have nevertheless included Ar ages in these figures, as most of them show a pronounced peak at ca. 35 Ma for Penninic units. (See also Fig. 9 in von Blanckenburg & Davies 1995). So even taking Ar ages only into account, we see no basis for a Cretaceous High-P event in the Penninic continental rocks.

Cretaceous. Eclogite facies rocks occur mainly in upper Austroalpine basement units of the Eastern Alps (Koralpe, Saualpe, South-Ötztal nappe, Fig. 1). An attempt to date these by garnet Sm-Nd has yielded a 90 Ma age for the amphibolite facies metamorphism following the high-P phase, thereby giving a minimum age of the eclogite event itself (Thöni & Jagoutz 1992). Another minimum age of 88 Ma is given by the Turonian Flysch, into which lawsonite and glaucophane have been deposited (Winkler & Bernoulli 1986). However, it must be pointed out that for similar sediments phengites of Hercynian ages were reported recently (von Eynatten et al. 1995). The other occurrence of Cretaceous high-P metamorphism is the Sesia-Lanzo Zone of the Western Alps. Here, the age evidence is even more vague, as it is mainly based on Ar phengite dating. One garnet Rb-Sr age of 115 Ma was reported (Oberhänsli et al. 1985), but a note of caution must be issued as this garnet contained unusually high Sr concentrations. Overall, high-pressure metamorphism must have taken place between 115 and 95 Ma in the Austroalpine.

Tertiary. Numerous ages of 60 to 50 Ma exist for Penninic blueschist facies ocean sediments and metamorphic basalts (Fig. 3). New data have been reported recently from blueschist facies calcschists from within this range (Takeshita et al. 1994). Ages from continental eclogite facies to coesite facies rocks vary between 45 and 30 Ma.

Alternative explanations for the Cretaceous high-P metamorphism involve "tectonic erosion" of parts of the overriding plate in a subduction melange (Polino et al. 1990). Other exhumation mechanisms are extensional exhumation from below a thickened orogenic wedge (Platt 1986), but this mechanism does hardly explain exhumation from mantle depths; or corner flow (Cowan & Silling 1978), but in this mechanism it is not clear what the "buttress" is that is required to induce the return flow. Reviews of exhumation mechanisms are given by Wheeler (1991) and Platt (1993), excluding slab break-off though.

2.3 Thermal metamorphism

Models for the loss of the lithospheric root of mountain belts predict significant consequences for the metamorphic evolution of orogenic belts (Sandiford 1989, Platt & England 1994). The main consequence is that rapid uplift and exhumation will be induced by the mechanical reequilibration of the orogenic edifice. The resulting near-isothermal decompression may therefore cause regional-metamorphic reactions. On a more local scale, advection of heat by melts can be important. These issues have not been addressed thoroughly for the case of the Alps yet. Some extended disussion is therefore required here.

Cretaceous. Cretaceous greenschist facies metamorphism is widespread in the Austroalpine of the Eastern Alps (Fig. 1). Amphibolite facies rocks occur in the Schneeberger Zug of the Ötztal nappe, southeast of the Tauern Window, and in the Kor- and Saualpe. Eoalpine greenschist facies metamorphism has also affected the external Sesia-Lanzo Zone. Although numerous cooling ages of 90–70 Ma have been reported for the Eoalpine metamorphism from the Eastern Alps (Frank et al. 1987a, b; Hoke 1990) and in the Sesia-Lanzo Zone (Stöckhert et al. 1986) the peak metamorphic ages are much less well constrained. From the few growth ages compiled for figure 2 it would appear that both greenschist and amphibolites facies metamorphism took place between 100 an 85 Ma. In the case of thermal metamorphism, Ar overpressure seems to be much less of a problem and we thus regard the resulting K-Ar ages as more reliable than those from high-P rocks. Frank et al. (1987a) conclude that the amphibolite facies metamorphism peaked at 90 Ma in the Schneeberger Zug.

Tertiary. All Penninic nappes, the southernmost Helvetic sections and marginal areas of adjacent Austroalpine (northernmost margin of the Sesia Zone, base of the Bernhard nappe) have been affected by Oligocene and younger Alpine metamorphism. The core of the Central Alps and the E and W Tauern Window, respectively, have been affected by higher grade metamorphism. A compilation of ages from greenschist facies metamorphic zones, presumably reflecting mineral growth as the metamorphic grade did not exceed the closure temperature of the respective systems, displays a remarkably sharp peak at 35–40 Ma (Fig. 3). This peak was identified for the Western Alps already by Hunziker (1969). All greenschist facies data from figure 3 are from the Western- and Central Alps. From the Tauern Window, most isotopic ages are from areas where the closure temperatures have been exceeded. It is therefore unclear how far this 35 Ma event extends to the east. The striking features of the 35 Ma "event" are: a) a very sharp peak in time; b) large areal extent; c) coincidence with the peak in HP ages (Fig. 3); d) a lack of age differences between various thermal and baric conditions. Feature d) makes post-burial relaxation of geotherms unlikely as cause for the metamorphism as this would lead to diachronous thermal climax at different structural levels (Burton & O'Nions 1992). Simple heat conduction from the root following breakoff will have only a minute effect at higher structural levels. Features a) and c) together open the possibility that the HP thrust sheet, which cooled during uplift, heated the crustal rocks into which they rose. Most likely, however, is that we see a sharp deformational event superimposed upon an orogenic edifice which had already been heated by any of the above reasons. Note that almost all ages have been obtained from white micas, which will readily recrystallize when sheared during induced tectonic movements. Such a "phase of deformation" at 35–40 Ma was indeed suggested from the observation that these phengites often record penetrative deformation of the studied rocks e.g. (Steinitz & Jäger 1981, Chopin & Monié 1984, Monié & Chopin 1991). Following slab breakoff, the changed stress regime of the orogen, in conjunction with the rise of subducted thrust sheets, will induce significant thermomechanic processes. The 35–40 Ma event could record the associated movements.

The peak of amphibolite facies or higher grade metamorphism was at ca. 29 Ma according to figure 3 (or between 32 and 20 Ma, e.g. Merle et al. 1989, von Blanckenburg et al. 1989, Vance & O'Nions 1992, Christensen et al. 1994). Merle et al. (1989) call this time interval the "high temperature deformation". Because these higher temperatures have been recorded at deeper structural levels, we could in fact have a component of retarded heating at deeper level (Burton & O'Nions 1992). An additional possibility is vertical heat transport by the rapid exhumation of the Central Alps and Tauern Window during backthrusting (Merle et al. 1989, Schmid et al. 1996). Rapid exhumation following loss of the lithospheric root could lead to a transient heat peak of high-T-low-P metamorphism (Platt & England 1994). The most likely cause for the late high-grade metamorphism, however, is heat advection by granitoid intrusions at 32–30 Ma (Schmid et al. 1996). This situation could have been similar to Cretaceous metamorphism in the western US Cordillera: localized peak metamorphism and deformation of the upper 15 km of crust coincides with the intrusion of granites and pegmatites at 90–70 Ma (Miller & Gans 1989), the granites being the heat source for the metamorphism. Close to the Periadriatic Lineament, the density of plutons could increase with depth below the present erosion level, thereby increasing the intensity of the heat advection.

Obviously, numerous alternative explanations for the regional metamorphism are on offer. Most of them, such as thermal reequilibration after thrusting, have been mentioned above and could well have acted even without slab breakoff. This would hold for both the Austroalpine in the Cretaceous, as for the Penninics in the Tertiary. In both cases the metamorphism could simply be the result of exhumation of partially subducted continental crust. Perhaps the most compelling evidence for slab breakoff is the coincidence of the high-T metamorphism with magmatic activity in both cases.

2.4 Orogen Deformation

It has been discussed at length in the literature that the loss of a dense lithospheric root will elevate the potential energy of an orogen (England & Houseman 1988). Rapid uplift may result and the orogen will start to "spread under its own weight". This implies extensional deformation or "extensional collapse" (Dewey 1988). Quantification of this process for orogenic belts has been presented in the literature (Sandiford 1989, Sandiford &

Powell 1990, Platt & England 1994). In the case of the Alps the situation is even more complicated, as ongoing compression is likely to have induced east-west extension both in the Cretaceous as well as in the Tertiary (Ratschbacher et al. 1989, 1991; Froitzheim et al. 1994).

Cretaceous. For the Austroalpine it has been shown that a phase of imbrication was followed by a phase of east-west directed extension (Ratschbacher et al. 1989, Froitzheim et al. 1994). Schmid et al. (1996) assign an age range of 80 to 67 Ma to the "Ducan-Ela phase" of extension.

Tertiary. Extensional exhumation of metamorphic Penninics took place mainly in the Miocene, following the mainly Eocene to Oligocene compressional phase (Ratschbacher et al. 1989, 1991; Mancktelow 1992). As noted by Ratschbacher et al. (1991), extension in the Eastern Alps was by tectonic escape along east-west trending strike slip faults as well as extensional spreading, whereas in the Central Alps the exhumation mechanism is that of a "ductile pop-up" (Merle et al. 1989).

As discussed (Ratschbacher et al. 1991) the Tertiary extensional events could be due to lateral tectonic escape, gravitational spreading or lateral transpression (Schmid et al. 1989) induced by the North-South directed forces imposed by the Adriatic indenter. Such a process will be very diffcult to distinguish from similar effects resulting from extensional collapse after loss of the lithospheric root. It would seem that the Tertiary timing is at odds with slab breakoff (at ca. 45 Ma, von Blanckenburg & Davies 1995) as a very likely cause for extension from 30–10 Ma. The link could be, however, the time gap necessary for heat transported after loss from the root by the various processes. This could take several tens of Myr (Sonder et al. 1987).

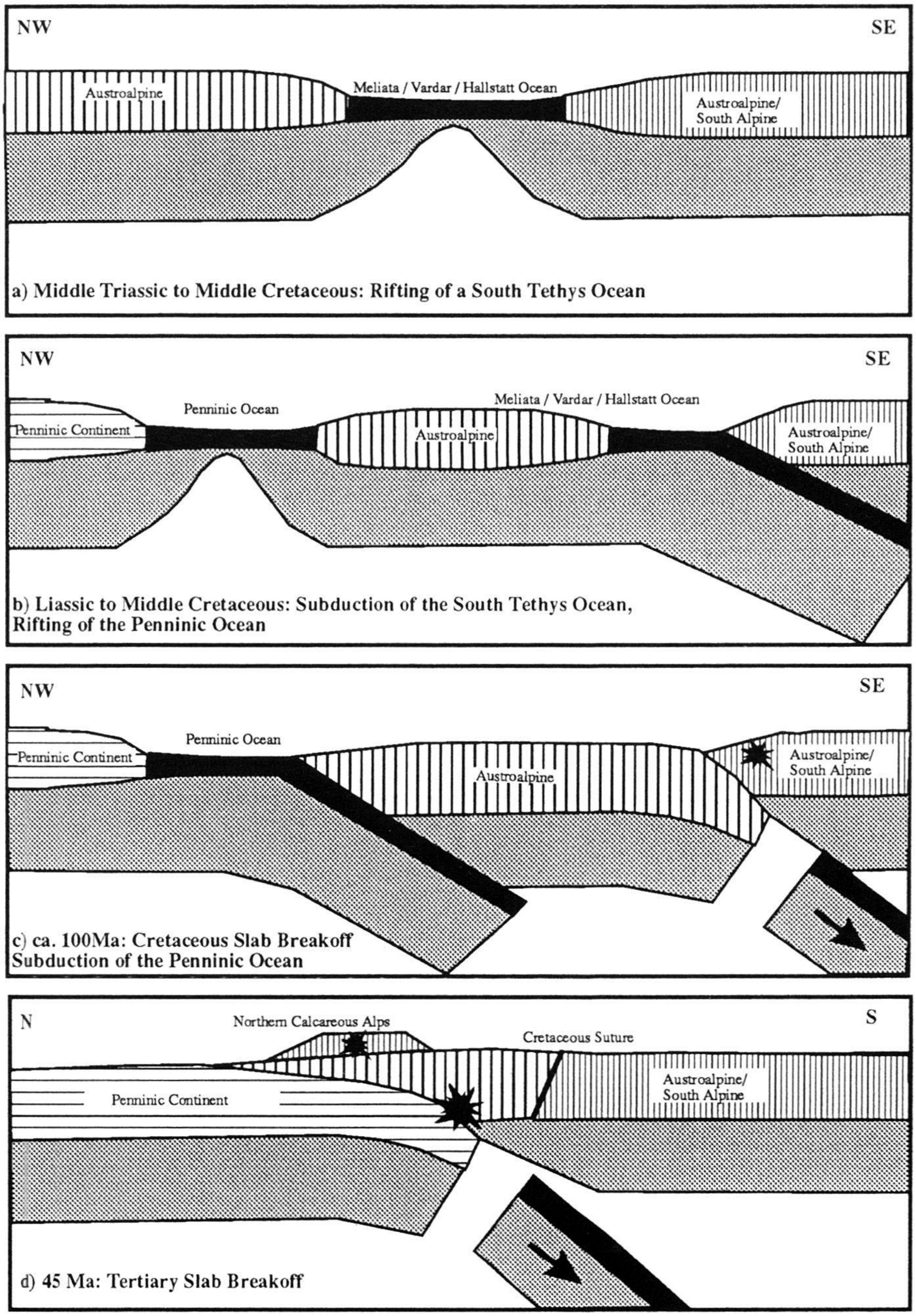
2.5 Erosion

The rapid uplift following loss of the mantle root will induce extensive erosion of the elevated orogen. Also, the extensional processes discussed above will allow basins to form where the erosional detritus can be deposited. Wortel & Spakman (1992, Fig. 2) suggest that slab breakoff will induce subsidence in the foreland due to the flexural rigidity of the short remaining continental slab.

Cretaceous. Basins filled with clastic sediments have formed from 90–60 Ma in the Eastern Alps ("Gosau") (Faupl et al. 1987). These have been interpreted as the result of orogenic extension (Ratschbacher et al. 1989).

Tertiary. The most immediate witness of Oligocene erosion was the postulated rapid uplift of the Bergell area at 30 Ma (Giger & Hurford 1989) and the "Augenstein Peneplain" of the Eastern Alps (Ratschbacher et al. 1991). The most obvious depositories of erosional products were the Molasse basin in the north and the Po basin in the south, respectively, which formed in the Oligocene (ca. 35 Ma).

Obviously neither the formation nor the filling of these basins is exclusive to slab breakoff. In particular the formation of a foreland basin is an ingredient of any orogenic belt. It is thought to be caused by bending of the rigid lithosphere under the load of the orogen (Homewood et al. 1986). Perhaps the real link to slab breakoff is the fact that erosion rates were indeed high both in the Cretaceous as well as in the Tertiary following the postulated breakoffs.



a) Middle Triassic to Middle Cretaceous: Rifting of a South Tethys Ocean

b) Liassic to Middle Cretaceous: Subduction of the South Tethys Ocean, Rifting of the Penninic Ocean

c) ca. 100Ma: Cretaceous Slab Breakoff Subduction of the Penninic Ocean

d) 45 Ma: Tertiary Slab Breakoff

Fig. 5. Cartoon showing the postulated spreading, subduction and breakoff of a south-Tethys ocean in the Cretaceous (following Neubauer et al. 1995) and a Penninic ocean in the Tertiary. Note that for clarity it is not shown that magma will be emplaced in both the formerly downgoing and the overriding plate, due to oversteepening of the suture.

3. Discussion and Conclusions

Following Thöni and Jagoutz (1993) we have explained all Cretaceous orogenic events affecting the Austroalpine with the collision following the closure of the South-Tethys Vardar-Meliata-Hallstatt Ocean (Neubauer et al. 1995). Following Froitzheim et al. (1994) and Schmid et al. (1996) we have also postulated that these Cretaceous events were distinct in time from those in the Tertiary. This separation is also based on an interpretation of Cretaceous high-pressure ages in the Penninics as being due to excess argon (von Blanckenburg & Davies 1995).

This two-orogeneses model has considerable advantages over other scenarios which explain the Alpine convergence as a single subduction process from 120 to 30 Ma, with concurrent subduction below and exhumation on top of an orogenic wedge (e.g. Polino et al. 1990). The model of Polino et al. has the inherent difficulty of subducting large parts of the overriding plate (Austroalpine) to mantle depths. "Subduction erosion" was invoked to achieve this. In the two-orogeneses model the eclogite facies Austroalpine was the continental margin that followed the South-Tethys Ocean into the mantle and any convergence between the Cretaceous and the Tertiary continental collisions was accomodated by subduction of oceanic lithosphere (Fig. 5). Due to different interpretation of high-pressure ages, this model is also incompatible with Avigad et al's (1993) reconstruction.

The Sesia-Lanzo zone of the Western Alps has many similarities with some Austroalpine units of the Eastern Alps, most notably in metamorphic history, but also in composition (Thöni & Jagoutz 1993). Obviously the palinspastic extension of the postulated South-Tethys Ocean up to the present Western Alps is not straightforward. Thöni & Jagoutz (1993) assume that this oceanic basin extended to about the present boundary between Eastern Alps and Western Alps. However, lateral displacements along a Proto-Periadriatic Lineament, which could have been the suture following the Eoalpine collision, could have transported the Sesia Zone from the westernmost edge of the ocean to a more westward position (Thöni & Jagoutz 1993).

A simplified cartoon shows the postulated tectonic evolution (Fig. 5). Spreading of the Vardar-Meliata-Hallstatt Ocean took place from the middle Triassic on. Subduction of this ocean and spreading of the Penninic ocean took place from the Liassic to Middle Cretaceous (Neubauer et al. 1995). Between 110 to 100 Ma the southern ocean must have been closed and the first slab breakoff occurred. The Penninic subduction initiated sometime in the late Cretaceous and terminated at ca. 45 Ma with the second slab breakoff. Due to the thrusting of the Austroalpine Northern Calcareous Alps over the Penninics the igneous products of the Cretaceous (and more southerly) slab breakoff are now found in the north of the Alps.

The evidence for slab breakoff is compiled in table 1. Both the Cretaceous as well as the Tertiary orogenic events contain stunning similarities. The most obvious difference is the rather minute magmatic activity in the Cretaceous. It is not a requirement, however, that slab breakoff should produce large volumes of melt. Indeed, it can take place without production of melts at all (Davies & von Blanckenburg 1995). Altogether the evidence from the Cretaceous is much less obvious than in the Tertiary. This is mainly due to the lower density in data, but also due to the lack of paleogeographic records. For example, Dal Piaz et al. (1995) have arrived at quite a different reconstruction for the east-

Table 1. Cretaceous and Tertiary Expressions of Slab Breakoff or Alternative Processes

Geological Feature	Explanation by Slab Breakoff	Austroalpine (Cretaceous)	Penninics (Tertiary)	Alternative Explanation
Basaltic & Granitoid Magmatism	Partial Melting of lithospheric Mantle over hot Asthenosphere rising into Breakoff Gap (Basalts). Induced Crustal Melting (Granitoids)	Basanitic Lamprophyres in Northern Calcareous Alps (100Ma)	Periadriatic Lamprophyres and Granitoids (43-25Ma)	Whole Lithospheric Extension Removal of a thickened thermal Boundary Layer Lithospheric Delamination
Exhumation of High-P Continental Slices	Release of buoyant crustal Sheets at Mantle Depths during Subduction and ultimately by Heating following Breakoff	Eclogite Facies Rocks in Kor- and Saualpe, Ötztal Nappe (and Sesia Zone) (110-90Ma)	Eclogite and Coesite Facies Rocks throughout Penninic Nappes (50-30Ma)	Extensional Exhumation in a thickened orogenic Wedge Cornerflow
Thermal Metamorphism	Advection of Heat by rapid Exhumation following release of the dense Mantle Root Advection of Heat by Melts Conduction of Heat from Mantle	Greenschist Facies throughout Austroalpine Basement (and Sesia Zone) Amphibolite Facies in Schneeberger Zug, SE of Tauern Window, Kor-and Saualpe (100-85Ma)	Greenschist Facies in Penninic Units (40-33Ma) Amphibolite and higher Facies in Central Alps and Tauern Window (33-25Ma)	Equilibration of Geotherms following Thrusting and Exhumation
Crustal Extension	Mechanical and isostatic Reequilibration (Collapse) of thickened continental Edifice following Release of the dense Mantle Root	East-West directed extensional faults throughout Austroalpine (90-70Ma)	East-West directed extensional faults exhuming Central Alps and Tauern Window (30-10Ma)	"Collapse" of a thickened orogenic wedge Extension during continuing Convergence
Basins filled with Erosion Products	Rapid Uplift of Orogen following Loss of Mantle Root leads to high Erosion Rates	Gosau Basins in Eastern Alps (90-60Ma)	Molasse and Po Basin (35-10Ma)	Flexural Bending of Fore- and Hinterland

ern edge of the early Cretaceous Alps. This means that the result of the Cretaceous slab breakoff test must remain rather inconclusive. The overall similarities of both orogenesis, however, make similar causes to their surface expressions very likely. Future acquisition and compilation of geochemical, sedimentological, structural and geochronological data will show whether slab breakoff was the cause.

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