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Slab breakoff: A model for syncollisional magmatism and tectonics in the Alps

Friedhelm von Blanckenburg

Department of Earth Sciences, University of Cambridge, Cambridge, England

J. Huw Davies

Department of Earth Sciences, University of Liverpool, Liverpool, England

Abstract. Slab breakoff is the buoyancy-driven detachment of subducted oceanic lithosphere from the light continental lithosphere that follows it during continental collision. In a recent paper *Davies and von Blanckenburg* [1994] have assessed the physical conditions leading to breakoff by quantitative thermomechanical modeling and have predicted various consequences in the evolution of mountain belts. Breakoff will lead to heating of the overriding lithospheric mantle by upwelling asthenosphere, melting of its enriched layers, and thus to bimodal magmatism. Breakoff will also lead to thermal weakening of the subducted crustal lithosphere, thereby allowing buoyant rise of released crustal slices from mantle depths. In this paper we present a test of this model in the Tertiary evolution of the European Alps. In the Alps, both basaltic and granitoid magmatism occur between 42 and 25 Ma, following the closure of oceanic basins by subduction and continental collision. The granitoids are now well established to result from mixing of basalt with assimilated continental crust. To identify the tectonically crucial origin of the partial mantle melts, we have compiled all published geochemical and isotopic data of numerous mafic dykes occurring throughout the whole Alpine arc. Their trace element and isotopic composition suggests that they have been formed by low-degree melting of the mechanically stable lithospheric mantle. We see no evidence for melting of asthenospheric mantle. It was thus not decompressed to depths shallower than 50 km. Once initiated, rapid lateral migration of slab breakoff will result in a linear trace of magmatism in locally thermal weakened crust. This explains why all Alpine magmatic rocks intruded almost synchronously along a strike-slip fault, the Periadriatic Lineament. A compilation of ages from Penninic high-pressure rocks subducted to depths of up to 100 km shows that subduction took place at circa 55-40 Ma, followed by uplift at 40-35 Ma. From the short time interval between their uplift and the onset of magmatism we infer that both processes have been induced by the breakoff. The slab breakoff model fulfills its predictions in the case of the Alps and therefore supports the assumptions made in the theoretical model on a geological basis. We believe that the characteristic association of magmatic activity with the return of high-pressure rocks to the surface allows the identification of this process in the Earth's mountain belts.

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1. Introduction

One of the well-known attributes of orogenic belts is syncollisional magmatism. An ever increasing isotope-geochemical database of such magmatic rocks has shown the involvement of partial mantle melts in many cases. This is almost a contradiction in a tectonic setting where geotherms are severely depressed by the lithospheric thickening. Extension of the lithosphere could generate partial mantle melts [*McKenzie and Bickle*, 1988]. However, intrusion of magma in compressive rather than extensional stress fields is becoming an increasingly evident emplacement mode [*Hutton and Reavy*, 1992]. In the past years, formation of these melts has been explained by a disturbance of the lithospheric root of mountain belts, such as delamination [*Bird*, 1979] or convective removal of the thickened thermal boundary layer [*Houseman et al.*, 1981]. However, these models take neither the oceanic subduction nor subduction of continental lithosphere to mantle depths into account, which precedes continental collision if a passive continental margin is subducted. Furthermore, field evidence or geochronological data in many mountain belts seem to indicate that the intrusion of granitoids postdates the emplacement of uplifted high-pressure nappes into midcrustal levels [*Davies and von Blanckenburg*, 1994].

In a recently published model, *Davies and von Blanckenburg* [1994] (also *von Blanckenburg and Davies* [1992]) have explained these features by slab breakoff. Slab breakoff will occur when light continental lithosphere follows dense oceanic lithosphere into the subduction zone. This situation of opposing buoyancy forces at depth will create strong extensional forces within the slab, resulting in a narrow mode of rifting and ultimately tearing off and falling away of the oceanic slab. The conditions for breakoff have been obtained from modeling of lithospheric strength versus buoyancy forces. The resulting rift will be filled by hot, uprising asthenospheric mantle, which will impinge upon the lithospheric mantle of the overriding plate. The conductive heating will lead to partial melting of enriched metasomatic layers within the lithospheric mantle, producing alkaline, ultrapotassic, or calc-alkaline basalts. These will rise into the crust, where they, in conjunction with thermotectonic effects, lead to crustal melting and thus to bimodal magmatism. Before breakoff, thermal weakening of subducted crust may allow layers to detach from their underpinnings and accrete to the overriding plate [*van den Beukel*, 1992]. When subducted to mantle depth, such thrust sheets will ultimately be released by the heating, hence weakening, and declamping during breakoff. They can rapidly rise as buoyant sheets back into the crust, due to their density contrast with the surrounding mantle, and will probably use the subduction thrust pathway. Oversteepening of the initial suture and backpropagating of thrusts during continental collision will concentrate the visible effects in the center of the orogen, with intrusions emplaced in both the overriding and the formerly downgoing plate, respectively. Other results of breakoff, not assessed in detail by *Davies and von Blanckenburg* [1994], involve the general change in potential energy of the orogen after the loss of the heavy root, which may lead to development of topography, erosion, possibly extensional deformation, and associated thermal metamorphism.

Slab breakoff will thus create a combination of characteristic features of mountain belts, which are distinct from those suggested for other mechanisms to produce synorogenic magmatism, such as delamination [*Bird*, 1979], thermal boundary layer removal [*Houseman et al.*, 1981], or lithospheric extension [*McKenzie and Bickle*, 1988]. The combined appearance of these characteristic features will enable the identification of the slab breakoff process as an outstanding step in the tectonics of orogenic belts: (1) bimodal magmatism comprising basaltic partial mantle melts on the one hand and granitoids, most likely formed by lower crustal melting and with a mantle parentage, on the other hand, (2) rapidly uplifted and later exhumed high-pressure or ultrahigh-pressure rocks, (3) regional metamorphism, (4) extensional structures, (5) the products of erosion in intramontane or adjacent basins.

The Tertiary evolution of the European Alps provides an ideal testing ground for the applicability of this model to the tectonics of orogenic belts: the enormous wealth of geological, geophysical, and isotopic data makes the Alps one of the best studied mountain belts worldwide. The subduction of both oceanic and continental crust to mantle depths is proven by the occurrence of eclogites and eclogite facies crustal rocks [*Coward and Dietrich*, 1989; *Monié and Chopin*, 1991; *Reinecke*, 1991]. Both granitic and mafic magmatism occur during the climax of continental collision (40-25 Ma). The mantle origin of the basaltic endmembers of the intrusions is now well established due to isotopic studies [*Kagami et al.*, 1991; *von Blanckenburg et al.*, 1992]. Thermal metamorphism occurs synchronously [*Hunziker et al.*, 1989; *Schmid et al.*, 1989; *von Blanckenburg et al.*, 1989, and references therein].

In this paper we will test the model of slab breakoff [*Davies and von Blanckenburg*, 1994] in the Alps. Because the most valuable tracers of subcrustal processes in the root of collision zones are partial mantle melts, we will first focus on the basaltic magmatism and derive its mantle source. Second, we will discuss the timing and mechanism of the uplift and exhumation of high-pressure metamorphic crustal rocks. Third, we will discuss

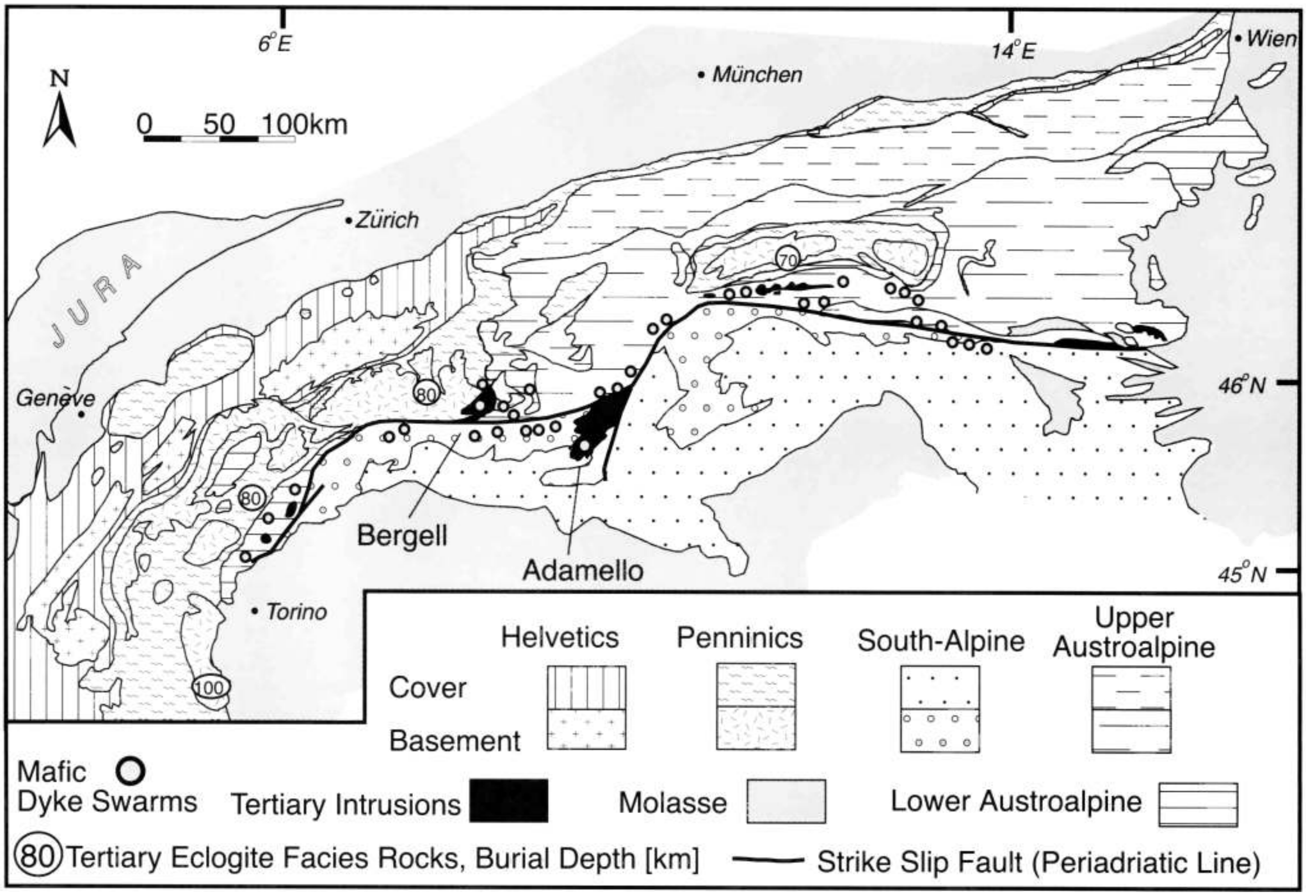

Figure 1. Tectonic map of the Alps.

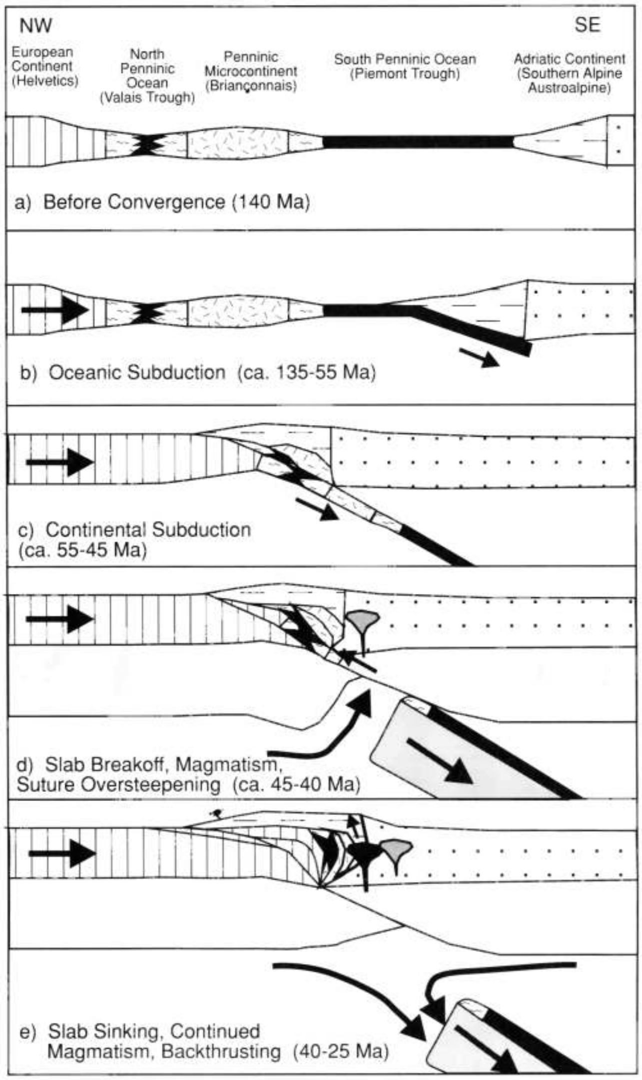

Figure 2. Tentative cartoon illustrating the tectonic evolution of the Alps, including the postulated breakoff of the subducted slab. Note that continental crust has been divided into normal crust and thinned continental crust. (a) Prior to convergence. (b) Oceanic subduction; all Cretaceous subduction of continental crust and accretion is omitted for clarity. (c) Thrust sheets of both oceanic and continental Penninic crust are underplated below the overriding plate, from where they are exhumed later on. (d) Dense oceanic lithosphere becomes detached from the buoyant continental lithosphere, thus bringing hot asthenospheric mantle to the base of the mechanical lithosphere. The resulting magma initially intrudes the overriding plate. The initial suture becomes oversteepened, leading to backpropagating of thrusts. Note also that layers of the deeply subducted continental crust have become unclamped and commence rapid uplift into the base of the crust. (e) The detached slab now sinks into the mantle, leading to continuous asthenospheric flow below the lithospheric mantle, thereby heating and partially melting it. Increased oversteepening leads to backthrusting along the Periadriatic Lineament, thereby allowing a migration of plutonic activity into Penninic thrust sheets.

some associated aspects of orogen deformation. The aim is to present a tectonophysical model which explains some of the still unexplained features of the geological record of the Tertiary Alps.

2. The Alps

The Alps (Figure 1) are the result of the closure of oceanic basins followed by continental collision [*Trümpy*, 1980; *Coward and Dietrich*, 1989]. At least two oceanic basins ("Piemont" and "Valais" trough) formed from the early Jurassic (circa 190 Ma) until circa 100 Ma (Figure 2a) [*Trümpy*, 1980]. They were separated by a peninsula of thinned continental crust ("Briançonnais"). Both the northern ("European") and the southern ("Adriatic") continental margin, and probably the northern Valais trough as well, consisted of thinned continental crust. Starting at circa 135 Ma, convergence between the Adriatic microplate (a promontory of Africa) and Europe initiated subduction of oceanic crust below the Adriatic continent (Figure 2b). During this process, thrust sheets were separated from the southern basement and thrusted as nappes ("Austroalpine") over both oceanic basins and peninsulars ("Penninic"). No remnants of any subduction magmatism are observed within this time interval. In the Eocene, Adria moved north to northwestward and closed the oceanic basins (Figure 2c). At circa 50 Ma the last sediments formed in the Valais trough, and continental collision was underway [*Trümpy*, 1980]. Some *Austroalpine* units, such as the Sesia zone, had already undergone Cretaceous high-pressure metamorphism [*Hunziker* et al., 1989]. *Polino et al.* [1990] ascribe this to "subduction erosion" of the Adriatic continental margin. Concerning the subduction of Penninic oceanic and distal European continental crust, there is now an increasing database confirming its Eocene to Oligocene age [*Monié and Philippot*, 1989; *Christensen et al.*, 1994; *Tilton et al.*, 1991; *Becker*, 1993], all ages ranging between 55 and 38 Ma. The full evidence for Tertiary high-pressure metamorphism in the Penninics is presented in section 4. Magmatism, both basaltic and granitic, occurred while the collision was in full progress, and ranged from 42 to 25 Ma (Figure 2d and 2e). Magmatism was accompanied by north-south convergence and thermal metamorphism in the Penninic units. After the Oligocene events, convergence continued up to the present day, and formed the deep root now observed below the Alps [*Müller*, 1989]. The cause for the Tertiary magmatism is still debated and is the main topic of this paper.

3. Alpine Magmatism

In this section we evaluate on the basis of published geochemical and geochronological data whether the timing and characteristics of the Alpine magmatism is compatible with the breakoff model. Using isotopic and trace elemental compositions we will derive the mantle sources leading to the partial melts.

3.1. Types, Occurrence, and Ages of Magmatic Rocks

All Tertiary magmatism is confined to a narrow belt immediately to the south and north of the Periadriatic Lineament (Figure 1). Several calc-alkaline plutons exist. They consist

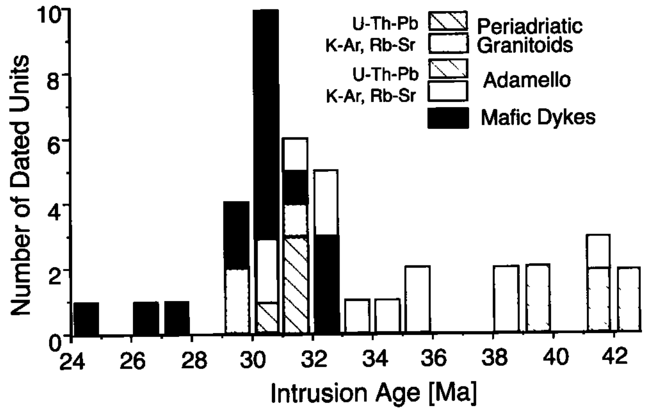

Figure 3. Histogram displaying intrusion ages of Tertiary magmatic rocks. Every dated intrusive unit or dyke has been assigned one entry only. Mafic dyke dates are K-Ar and Rb-Sr mineral ages [*Deutsch*, 1984; *Diamond and Wiedenbeck*, 1986; *Dal Piaz et al.*, 1988]. K-Ar and Rb-Sr mineral ages (white mica and biotite) on intrusions are from *Borsi et al.* [1979] and *Del Moro et al.* [1983b]. U-Th-Pb accessory mineral ages [*Barth et al.* 1989; *Hansmann and Oberli*, 1991; *von Blanckenburg*, 1992] are emphasized graphically, as they are considered as particularly robust against perturbations. Note that the ages of mafic dykes from south of the Tauern Window [*Deutsch*, 1984] are based on both K-Ar and Rb-Sr mineral isochrons from areas which have not been affected by the Tertiary metamorphism (according to a compilation of mineral ages in this area, biotite ages have not been reset [*Hoke*, 1990]). The dyke ages should therefore represent true intrusion ages.

mostly of tonalite and granodiorite. The largest and most famous are the Bergell and Adamello intrusions. Early mafic differentiates (gabbroic cumulates) are abundant only in the southern Adamello massif, while smaller occurrences are also present in the Bergell. Other mafic rocks occur in these intrusions as dykes and xenoliths. A small leucogranitic pluton (Novate) is located immediately west of the Bergell intrusion and is not related to the events forming the calc-alkaline intrusions. Numerous lamprophyric and acidic dykes occur along the whole length of the Periadriatic Lineament. A full account of the geological position of all Periadriatic intrusives is given by *Exner* [1976].

Intrusion ages, as compiled from the literature, display a pronounced and sharp maximum of plutonic and subvolcanic activity between 29 and 33 Ma (Figure 3). Among nine dated mafic dykes, three younger ages of between 24 and 27 Ma have been reported [*Deutsch*, 1984].

3.2. Geochemical and Isotopic Constraints on Magma Sources

Combined $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ data have been reported for the intrusives and a few associated dykes (Figure 4). The range of ε_{Nd} from +4 to -9 and $^{87}Sr/^{86}Sr$ from 0.704 to 0.712 is a typical mixing array between mantle and crustal isotopic values. This is due to simultaneous fractional crystallization of mantle melts and assimilation of crust (AFC) with the exception of the Novate leucogranite, which is probably the only product of crustal fusion alone [*von Blanckenburg et al.*, 1992]. The AFC process in these intrusions has been discussed at length in the literature [e.g. *Del Moro et al.*, 1983a; *Kagami et al.*, 1991; *von Blanckenburg et al.*, 1992] and shall not be repeated here.

The most valuable indicators of mantle melting are the mafic dykes. In order to minimize the effects of fractional crystallization and possibly crustal contamination we have restricted our attention to the basaltic to basaltic andesitic dykes ($SiO_2 \leq 56$ %). Among these, we have distinguished a group least likely to have been strongly modified by these processes (MgO > 6 %).

Figure 5 shows K_2O versus SiO_2 for the mafic dykes. The bulk of the dykes plotted are calc-alkaline, high-K calc-alkaline, and shoshonitic in nature. The few points plotting in the low-K field are high-alumina basalts, and hence calc-alkaline, rather than true tholeiites. The literature data shows that most of the ultrapotassic samples are also the highest in Cr (600-800 ppm) and Ni (300-460 ppm, [*Venturelli et al.*, 1984] and are therefore rather unfractionated primary melts. The vectors in Figure 5 point to the processes contributing to these variations; high K_2O can be produced either by mantle metasomatism or by a decrease in the partial melt fraction. Increase in SiO_2 with modest increase in K_2O points to fractional crystallization or crustal contamination. The latter process was probably operative in forming the high-K calc-alkaline melts.

Sr isotopes (Figure 6) and rare earth element (REE) spectra (Figure 7) can be used to discriminate between these processes. The calc-alkaline samples display low to modest light REE (LREE) enrichment. The lowest REE concentrations are given by the picrobasalts of the Adamello intrusion, which are con-

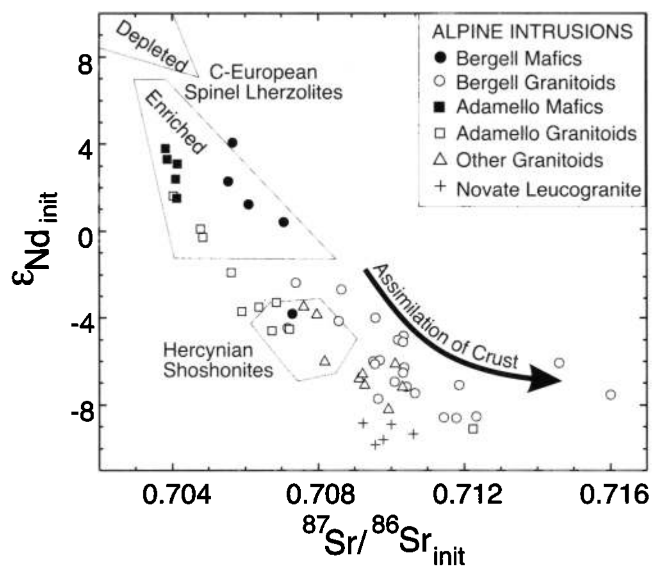

Figure 4. Initial ε_{Nd} versus initial $^{87}Sr/^{86}Sr$ for Periadriatic intrusions and dykes. Mafic samples are with $SiO_2 \leq 56$ wt %, and mafic mineralogy. Data are after *Juteau et al.* [1986], *Barth et al.* [1989], *Kagami et al.* [1991], *Oschidari and Ziegler* [1992], and *von Blanckenburg et al.* [1992]. For reference, fields are shown for central European incompatible element depleted and enriched spinel lherzolite xenoliths as compiled by *Wilson and Downes* [1991] and for central European shoshonites [*Turpin et al.*, 1988], which have been time corrected from 295 to 30 Ma assuming a $^{147}Sm/^{144}Nd$ of 0.13 and $^{87}Sr/^{86}Sr$ of 0.2 for their mantle source.

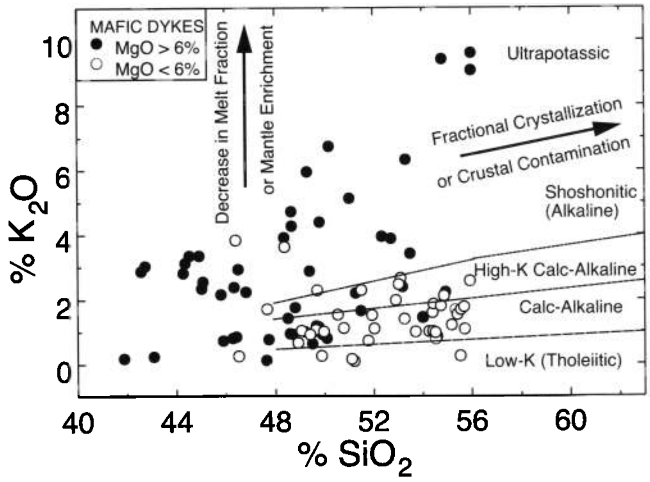

Figure 5. $\%K_2O$ versus $\%SiO_2$ for mafic dykes ($SiO_2 \leq 56$ wt %). Data are from *Gautschi and Montrasio* [1978], *Beccaluva et al.* [1979], *Ulmer et al.* [1983], *Deutsch* [1984], *Venturelli et al.* [1984], *Dal Piaz et al.* [1988], *Diethelm* [1990], *Müller et al.* [1992], and *von Blanckenburg et al.* [1992].

sidered to be primary parental melts [*Ulmer et al.*, 1983]. According to melting experiments, they could have been produced by partial melting of a wet fluid-metasomatized garnet lherzolite at a temperature of about 1200°C and a depth of between 50 and 80 km [*Ulmer*, 1987]. The $^{87}Sr/^{86}Sr$ of 0.704 from these dykes [*Del Moro et al.*, 1983a; *Kagami et al.*, 1991] is the lowest of all samples. The degree of enrichment in large-ion lithophile (LILE), high field strength elements (HFSE), REE, and $^{87}Sr/^{86}Sr$ in other dykes above this "base level" could, in theory, be explained by AFC. Given that LREE concentrations in average crustal rocks are rarely much more than 100 times chondrite, however, large amounts of crust would have to be assimilated to produce the enriched dyke spectra from a calc-alkaline one. In addition, to elevate $^{87}Sr/^{86}Sr$ from 0.704 in the calk-alkaline dykes up to 0.721 (Figure 6) in ultrapotassic rocks, and ε_{Nd} from +4 to -4 (Figure 4) would result in major element compositions with highly silicic compositions and could not be maintained in modestly differentiated basaltic rocks with high Cr and Ni concentrations. We are left to conclude that the extreme enrichment in these incompatible elements as well as the highly enriched Sr and Nd isotopes are a feature inherent to the magma source.

It is usually assumed that such strong enrichment in incompatible elements, which decay and produce isotopically "crustal" signatures in geological timescales, can be maintained only in the nonconvecting mechanical boundary layer of the lithospheric mantle. The convecting asthenospheric mantle would dilute and homogenize any enrichment [*McKenzie*, 1989]. In ε_{Nd}-$^{87}Sr/^{86}Sr$ space (Figure 4), samples from the depleted asthenospheric upper mantle should plot in the fields of depleted spinel lherzolites from nodules in central European alkaline volcanics [*Wilson and Downes*, 1991]. The fact that all samples are equal to or more enriched than the "base level" of ε_{Nd} = +4 and $^{87}Sr/^{86}Sr$ = 0.704, in conjunction with the fact that significant crustal contamination is excluded by major element chemistry, indicates absence of any asthenospheric imprint. Indeed, all calc-alkaline samples plot well within the field of the enriched lherzolites, and the "base level" isotopic signature could represent a moderately enriched lithospheric mantle. The shoshonitic and ultrapotassic samples ($^{87}Sr/^{86}Sr \leq 0.722$, $\varepsilon_{Nd} \geq -4$) are derived from an even more strongly enriched layer similar to the mantle source of Hercynian lamprophyres in central Europe [*Turpin et al.*, 1988] (Figure 4).

Further evidence against melting of asthenospheric mantle is provided by the flat heavy REE (HREE) spectra of all dykes (Figure 7). This arises from the fact that the subcontinental lithospheric mantle is assumed to have formed by strong initial depletion of upper mantle during the formation of basaltic crust and was later on metasomatized by melts or fluids rich in incompatible elements [*Frey and Green*, 1974]. The observed melts are then extracted from this enriched reservoir. Such a three-stage evolution was recently modeled for the source region of kimberlites [*Tainton and McKenzie*, 1994]. It was shown that the initial depletion of about 20% in the garnet stability field has the effect of quantitatively removing all Al and LREE and most of the Ca. Since the HREE are thus relatively enriched, they determine the shape of HREE in a later formed partial melt, which is rather flat. No other extraction process is capable of producing such flat HREE spectra. In contrast, the light REE will be strongly enriched, if the initially depleted matrix is later metasomatized by small- volume melt fractions originating in garnet peridotite of the underlying asthenospheric mantle [*McKenzie*, 1989]. Finally, to obtain the flat HREE spectra in the Alpine melts, melting at least partially in the spinel lherzolite field (<80 km depth) is required. Melting in the garnet field alone would retain the HREE.

We cannot assess how important sediment subduction has been in metazomatising the mantle wedge. Clearly, hydrous fluids released from subducted slabs may well carry LIL elements and therefore may alter the Sr and O isotopic composition of the overlying mantle as well as increase K, Rb, and Ba concentrations. Whether they can carry significant amounts of REE is still debated.

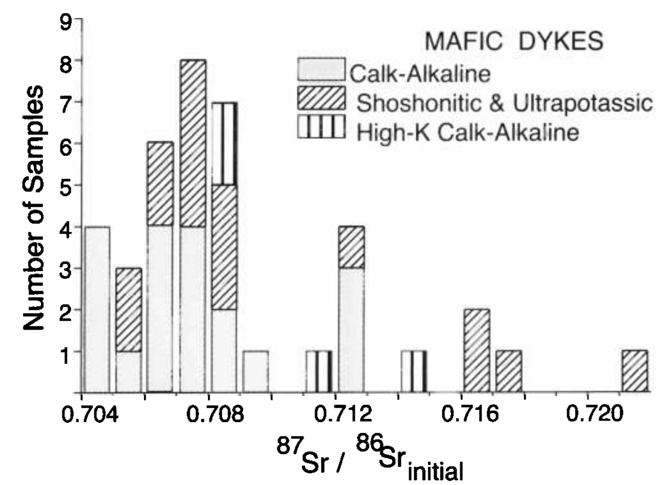

Figure 6. Initial $^{87}Sr/^{86}Sr$ for mafic dykes ($SiO_2 \leq 56$ wt %). The subdivision is after Figure 5. Data are from *Del Moro et al.* [1983a], *Deutsch* [1984], *Venturelli et al.* [1984], *Dal Piaz et al.* [1988], *Kagami et al.* [1991] and *von Blanckenburg et al.* [1992].

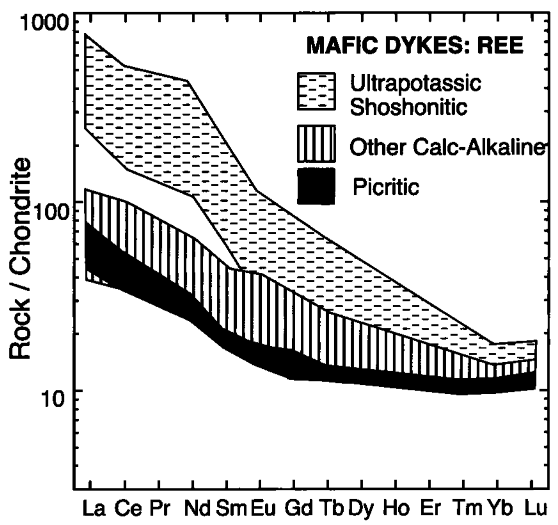

Figure 7. Rare earth element abundances in mafic dykes. Data sources are the same as for Figure 5.

3.3. A Model for Mantle Heating and Melting Following Breakoff

In the preceding section it was shown that the Tertiary Alpine magmatism originated in the mantle part of the lithosphere and that no asthenospheric melting is involved. This implies that the detachment took place at depths greater than 50 km, which would prevent the dry asthenospheric mantle from melting given the usual 1280°C potential temperature adiabatic geotherm below the continents [*McKenzie and Bickle*, 1988]. This conclusion is supported by the depths of about 100 km to which continental crust has been subducted [*Monié and Chopin*, 1991; *Reinecke*, 1991; *Becker*, 1993]. Once breakoff has occurred, hot asthenospheric mantle will be brought to the base of the mechanical lithosphere. Figures 8a and 8b display the results of one-dimensional models of heat conduction into the lithosphere from a base of 100 and 80 km, respectively, using the method of *Davies and von Blanckenburg* [1994]. To simulate the situation in the Alps, we have assumed breakoff at 45 Ma. This is the time at which high-pressure rocks were exhumed [*Christensen et al.*, 1994; *Becker*, 1993], and shortly thereafter the first intrusive rocks are emplaced in the Adamello batholith. We modeled a continuous supply of heat by the asthenospheric flow from 45 Ma up to 30 Ma, followed by equilibration of thermal conditions due to closing of the gap opened by removal of the falling slab, due to continued convergence (Figure 2e). The thermal equilibration was modeled as by *Bird* [1979].

We see that the critical temperatures for melting of metasomatized peridotite (1000-1100°C, [*Davies and von Blanckenburg*, 1994], Figure 5a), are obtained only between 100 and 80 km depth for the lithospheric base of 100 km (Figure 8a) but up to 60 km in the case of the 80-km-deep base (Figure 8b). Temperatures rise rapidly near the base, predicting the first melting from these deep layers at 42-40 Ma, and more slowly in shallowers levels, which will melt at 35-30 Ma. In the case of the 80-km base, the hot temperatures prevailing up to 30 Ma wane rapidly after the onset of thermal reequilibration, so that magmatism will cease at 25-20 Ma. The geochemical data require the top of the melting column to be at depths of < 80 km, which is required for the inferred melting of spinel lherzolite. This is achieved in the 80-km base model (Figure 8b). This implies that the whole mechanical boundary layer, which could have its thickness increased by underthrusting during the collision, must be thinned by the wedge flow during subduction and the detachment process to a thickness of less than 100 km. The overall duration of magmatism for 17 m.y. can therefore be explained by the asthenospheric flow induced by the sinking slab [*Davies and von Blanckenburg*, 1994, Figure 1d] which could slowly heat and partially melt the mechanical boundary layer, until continu-

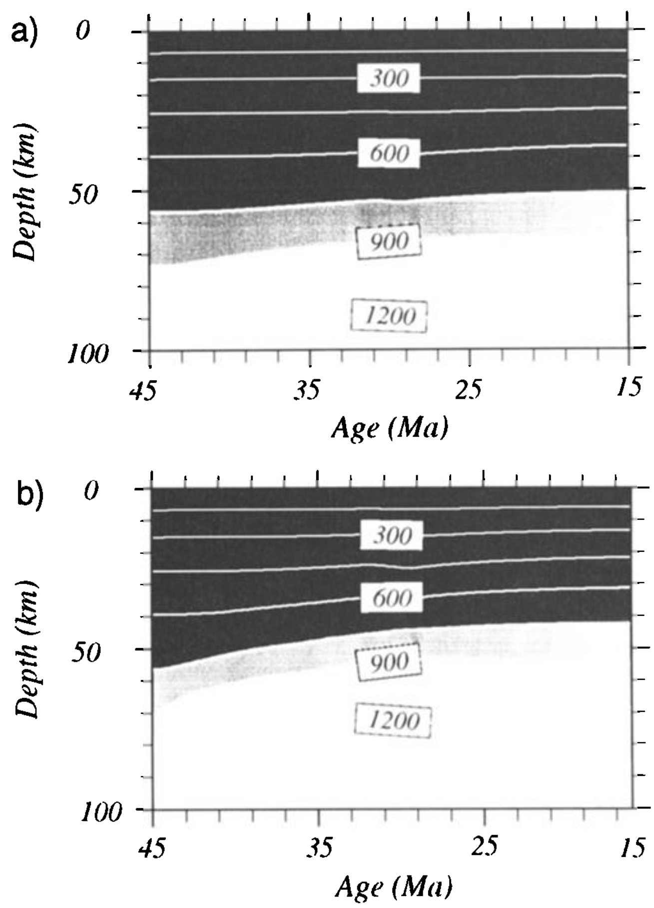

Figure 8. One-dimensional thermal models [*Davies and von Blanckenburg*, 1994] for conductive lithospheric heating following the emplacement of hot (1370°C) asthenosphere at (a) 100 km depth and (b) 80 km depth against mechanically stable lithosphere with a prebreakoff steady state thermal regime with a surface heat flow of 60mW m^{-2}, where 40% of the surface heat flow is accounted for from internal heat production in an upper crust 18-km-thick, while the radiogenic heat production in the 18 km thick lower crust is assumed to be 0.5μW m^{-2}. The radiogenic heat production in the mantle is set to zero. This results in an initial thermal gradient of 21°C/km at the top and 11.3° C/km at the base. The hot temperature was maintained from 45 to 30 Ma [*Davies and von Blanckenburg*, 1994] and was then allowed to reequilibrate [*Bird*, 1979] as the convergence continued. Note that the conditions for melting of enriched lithospheric mantle are achieved between 1100 and 1000°C. Note also that the thermal effects in the upper lithosphere, e.g., in the crust, are almost negligible.

ing convergence prevents further exposure of the lithospheric base to asthenosphere, so that temperatures start to equilibrate at circa 30 Ma.

As discussed [*Davies and von Blanckenburg*, 1994], enriched segments of the downgoing plate could partially melt during breakoff where they are exposed to the uprising asthenosphere, unless they have been depleted during the rifting leading to the formation of oceanic crust. In the Alps, this would have led to a migration of magmatism from north to south. However, because the reverse is the case (first intrusions in the southernmost Adamello intrusions, Figures 1 and 3), and because widespread crustal melting of exhumed high-pressure Penninic rocks is not observed, we believe that the end-member model of melting of the overriding plate is more likely. Nevertheless, should melting of subducted continental crust have occurred, it could have contributed to the metasomatism of the overriding lithospheric mantle.

4. High-Pressure Metamorphism

4.1. Timing

The association of exhumed high-pressure (HP) rocks with igneous rocks is diagnostic of the breakoff process. The issue of the timing of HP metamorphism therefore deserves an extensive discussion.

In the Alps the age of HP metamorphism is controversial. Various workers have suggested a Cretaceous ("Eoalpine") age for all HP metamorphism [e.g. *Hunziker et al.*, 1989], with continuous subduction and formation of an orogenic wedge from 120 to 40 Ma [*Polino et al.*, 1990], whereas recently, U-Pb ages of 40-30 Ma were obtained on coesite-bearing Dora-Maira schists [*Tilton et al.*, 1991], which have previously been dated at 110 Ma by ^{39}Ar-^{40}Ar [*Monié and Chopin*, 1991].

We believe that some of the confusion arises from two facts: (1) HP metamorphism in the Austroalpine nappes can have occurred earlier than that in Penninic nappes, given their different paleogeographic setting. We do not dispute the Eoalpine HP age (120-90 Ma) in the Austroalpine Sesia Zone [*Oberhänsli et al.*, 1985], Kor and Saualpe [*Thöni and Jagoutz*, 1992], or other Austroalpine units [*Hunziker et al.*, 1989]. A discussion of this Austroalpine HP metamorphism is not the topic of this paper. (2) ^{39}Ar-^{40}Ar or K-Ar ages from phengites, most often used for dating HP metamorphism, are often affected by homogeneously distributed excess argon, despite their plateaulike appearance [*Arnaud and Kelley*, 1994; *Li et al.*, 1994]. This explains why phengite Ar ages, despite their much lower closure temperature than, for example, garnet Sm-Nd, U-Pb, and Rb-Sr systems, give notoriously higher ages than these high-retentivity systems [e.g., *Monié and Chopin*, 1991; *Tilton et al.*, 1991; *Li et al.*, 1994], even from rocks which have been heated to 800°C, far in excess of their closure temperature. Although the systematics of high-retentivity minerals in HP rocks is far from well understood, we consider them as more reliable and will base our interpretation mainly on these results.

The main issue of this paper is the collision of the European continental margin with Adria, following closure of the Penninic oceans. We have therefore made an attempt to compile all HP ages from Penninic rocks in the Alps (Figure 9) excluding chronometers of unknown retentivity, such as paragonite or blue amphibole. Whereas a few scattered phengite Ar ages occur at 120-90 Ma, the majority of ages places the HP metamorphism and

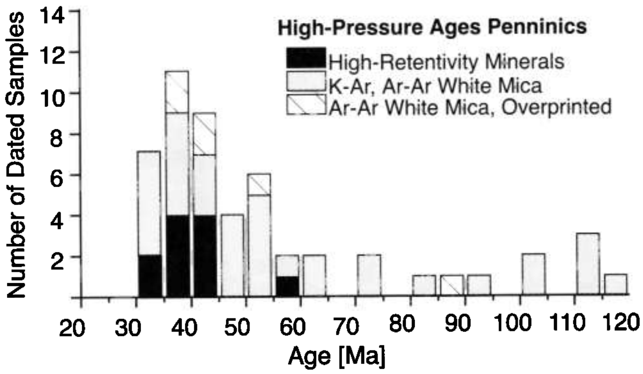

Figure 9. Compilation of isotopic ages from Penninic high-pressure units. Ages are normally derived from K-Ar and Ar-Ar dating of white micas, although the temperatures experienced by these rocks (450-750°C) by far exceed their assumed closure temperature (about 400°C). In contrast, "high retentivity minerals," such as garnet Sm-Nd or ellenbergerite U-Pb should record either growth or closure at very high temperatures (600°C). Minerals sensitive to excess argon, such as blue amphibole, with unknown retentivity, such as paragonite, or with uninterpretable degassing spectra have been omitted. Phengite data are from *Bocquet et al.* [1974], *Delaloye and Desmons* [1976], *Chopin and Maluski* [1980], *Chopin and Monié* [1984], *Monié* [1985], *Hurford and Hunziker* [1989], *Monié and Philippot* [1989], *Monié and Chopin* [1991], *Scaillet et al.* [1992], and *Zimmermann et al.* [1994]. Garnet and ellenbergerite data is from *Christensen et al.* [1994], *Tilton et al.* [1991], and *Becker* [1993].

cooling thereafter into the Eocene to Oligocene. A peak exists from 45 to 35 Ma. All high-retentivity chronometers give Tertiary ages. Note that Rb-Sr ages for cores of garnets dating the prograde HP path from the Tauern Window [*Christensen et al.*, 1994] give ages from 55 to 43 Ma. Sm-Nd garnet ages from the Central Alps [*Becker*, 1993] possibly date cooling during decompression at circa 40 Ma. Nevertheless, the actual HP metamorphism cannot have preceded cooling by much, so the age must be close to the maximum pressure event. All Cretaceous and intermediate ages are phengite Ar ages, which have a high probability to be elevated by excess Ar. Although it is entirely possible that some Penninic rocks were accreted below the overriding plate earlier than in the Tertiary, we believe that HP metamorphism in the exposed and dated Penninic rocks occurred between circa 55 and 30 Ma, with the main uplift and initial cooling from high temperatures taking place between 45 and 35 Ma. This interpretation is roughly in line with the youngest sediments in the Valais and Piemont trough being of Eocene age [*Trümpy*, 1980] and also with upper Cretaceous sediments overlying the coesite-bearing Dora Maira units [*Marthaler et al.*, 1986]. Of course, closure of the Tethyan basins need not have been simultaneous everywhere along strike in the Alps.

4.2. A Model for Uplift and Exhumation of High-Pressure Nappes

During subduction of continental crust, the downgoing slab will heat up, mechanically weaken, and move deeper adjacent to regions of higher density, such as the possible eclogite facies mafic lower crust of the overriding plate, and the lithospheric mantle. When the buoyancy forces created by the density contrasts exceed the strength of a continental rock, a thrust sheet may delaminate ("breakup") and accrete to the crustal base of the overriding plate [*van den Beukel*, 1992]. We have extended van den Beukel's model to subduction deep into the mantle, such as experienced by the Alpine very high pressure rocks. We envisage that delaminated rock piles will rise as "buoyant sheets" (or "pips", *Wheeler* [1991]) probably using the subduction thrust, because this is the zone of greatest weakness (Figure 10a). Boudins of eclogite will rise with their light matrix of silicic rocks [*England and Holland*, 1979]. This active uplift process will cease after arrival in the upper crust of the overriding plate, when the density contrast wanes. From hereon the nappes will be exhumed by a different process, such as extension [*Platt*, 1986] or erosion. Slab breakoff will facilitate this process, because of the strong heating and weakening during the necking of the plate (Figure 10b) and the unclamping of the rheological layers after the removal of the detached slab. So, possibly, HP thrust sheets will uplift throughout the subduction process, up

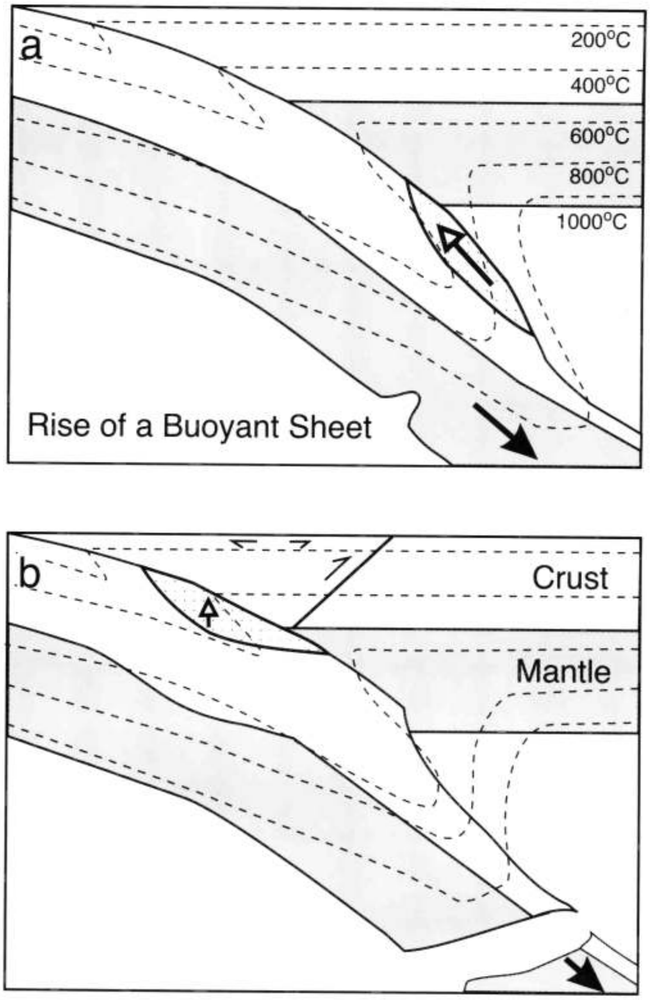

Figure 10. Cartoon showing rise of a buoyant sheet from mantle depth back into the crust of the overriding plate, from whereon an exhumation process such as extension or erosion will operate. (a) Before breakoff and (b) after breakoff.

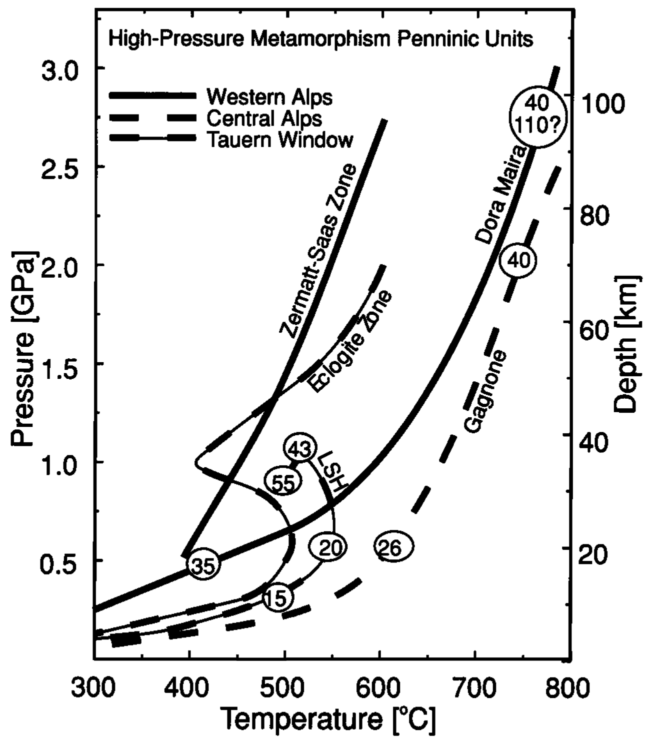

Figure 11. Pressure-temperature-time paths from high-pressure rocks in the Alps. The paths from the coesite-bearing units of Dora Maira are after *Monié and Chopin* [1991] and *Tilton et al.* [1991]. The path from the Zermatt-Saas Zone is from coesite-bearing subducted oceanic sediments [*Reinecke*, 1991]. The data of Gagnone are from *Becker* [1993]. The eclogite zone path of the Tauern Window is from *Zimmermann et al.* [1994]. The path from the Lower Schieferhülle (LSH) of the Tauern Window is after *von Blanckenburg et al.* [1989] and *Christensen et al.* [1994].

until when the breakoff process is in full progress. In the Penninics of the Alps, the short time interval between uplift of HP rocks and the onset of magmatism raises the possibility that slab breakoff was the event that triggered release of the buoyant thrust sheets.

The rising sheets will be bounded by colder material from both below and above during uplift (Figure 10). We expect them to be "refrigerated," so the decompression PT paths will be temperature down. This is principally observed on all very high pressure paths (Figure 11). Only at intermediate pressure, such as displayed by the paths from the Tauern Window, does the different exhumation process lead to heating during decompression.

5. Orogen Deformation

5.1. Emplacement of Intrusions and the Formation of the Periadriatic Lineament

The plutons and dykes are emplaced along a prominent fault zone with a backthrusting and a strike slip component, the Periadriatic Lineament (Figure 1). It is very probable that this fault zone was initiated with the formation of the magmas. The slab detachment process, once initiated, will rapidly migrate laterally ,at rates of 10km/m.y. to 1000km/m.y. [*Yoshioka and Wortel*, 1994]. It will therefore produce a linear zone of lithospheric heating and hence magmatism along the whole orogenic belt. The melts will weaken the lithosphere. The area overlying the breakoff line is therefore predestined to form a tectonic fault. In the case of the Periadriatic Lineament, the fault accommodated the continuing oblique convergence of the Adriatic plate relative to the European plate. The presence of the lineament encouraged the localization of the magmas and reinforced the localization of the displacements along itself as it became an ever greater point of weakness. The situation is likely to have resembled that of the Sumatra Arc today: there, oblique subduction results in a convergent component normal to the plate boundary and strike-slip faulting along a trench-parallel transcurrent fault located along an axis of a chain of active volcanoes [*Fitch*, 1972]. The coexistence of active volcanism and transcurrent faulting is explained by the zone of lithospheric weakness generated by the interplay of magmatism and faulting. In the case of the Periadriatic Lineament, pluton emplacement was facilitated by the enhanced mobility of granitic melts in a compressive environment [*Hutton and Reavy*, 1992]. A recent study of the Bergell tonalite has shown that the magma intruded into a compressive stress field [*Rosenberg et al.*, 1994]. A very similar setting was reported from the Pan-African Dom Feliciano belt of southern Brazil [*Tommasi et al.*, 1994]. Formation of an orogen-parallel shear zone was triggered by magma emplacement at depth and localized thermomechanical softening. Tommasi et al. discuss several causes for the melting. We suggest slab breakoff as additional option for formation of a linear magmatic arc with localized tectonic movements.

5.2. Backthrusting

Note that the intrusions occur both in the formerly overriding plate ("South Alpine, Austroalpine"), and, in the case of the Bergell intrusion, also in nappes of the downgoing ("Penninic") plate (Figure 1). We interpret this as being due in part to the fact that parts of the downgoing slab have been accreted below the overriding plate (Figure 2c, Figure 10), so that they can be reached by the uprising melts (Figure 2d).

More important though is the steepening of the initial suture once continental subduction is in progress (Figure 2c). Due to the local buoyancy of continental crust, increased resistive forces will lead to accommodation of compressive deformation by accretion of thrust sheets and backpropagation of thrusts at the front of the formerly overriding plate, at depths below the orogenic lid. This process will be strongly enhanced once the oceanic slab has detached, if convergence continues (Figure 2d). The virtual insubductability of continental crust will form an oversteepened thrust belt (Figure 2e). In the Alps this essentially leads to the formation of the southern steep belt, the backthrusting of the Central Alps over the Southern Alps along the Periadriatic Lineament [*Schmid et al.*, 1989; *Rosenberg et al.* 1994], and the syncompressive intrusion of granitoids into rocks of both the formerly downgoing and overriding plate [*Schmid*, 1992]. Note that also in the Eastern Alps, Periadriatic intrusions occur in the immediate proximity of the Penninic Tauern Window (Figure 1). We therefore believe that the described steepening must have acted along the whole Alpine arc.

The South Adamello intrusion is the only one to be emplaced initially at a more southerly position. The reasons for this could be (1) formation of South Adamello by a process other than slab breakoff, in which case our timescale for the onset of the event would have to be reassessed (we consider such a coincidence unlikely), (2) earlier breakoff, or initiation of breakoff below Adamello, and later elsewhere, (3) presence of melts everywhere along a broad zone, but only in South Adamello were the early ones emplaced near the surface, whereas more northward emplacement was facilitated and localized by later development of the Periadriatic Lineament, and/or (4) migration of the magmatic front from south to north, due to the oversteepening and backthrusting of the former suture toward the south above the stationary breakoff "hotspot" (Figure 2d and 2e). Again, only in the case of Adamello were the early melts emplaced at high levels. At the present stage we consider the third option as most likely.

5.3. Rapid Erosion and Continued Convergence

One of the consequences of the loss of the lithospheric root will be the rise of the orogen above its stable height [*Platt and England*, 1994], followed by erosion or extension [*Sandiford*, 1989]. Evidence is provided that the Bergell intrusion suffered very rapid exhumation and erosion, possibly involving glacial transport from great heights, immediately following its emplacement [*Giger and Hurford*, 1989].

It has been argued that the deep crustal root observed in deep reflection seismics below the Alps and other young orogenic belts yields evidence that delamination has not taken place [*Nelson*, 1992]. However, the deep root below the Alps [*Müller*, 1989] is the result of the Miocene to present-day convergence only, which has obscured any remnants of the detachment at circa 45 Ma. We suggest that a deep crustal root, such as that below the Alps today, will form only after slab breakoff has disabled the removal of continental crust to mantle depth by subduction.

6. Discussion

6.1. Thermal boundary layer detachment ?

Other mechanisms for the removal of the lithospheric root involve delamination of the whole lithospheric mantle [*Bird*, 1979] or convective removal of the thickened thermal boundary layer [*Houseman et al.*, 1981]. We can convincingly argue against delamination in the case of the Alps, because the associated deformation would affect a region of large aerial extent, such as the Tibetan or Colorado Plateau, and would result in huge amounts of crustal melting, because asthenospheric mantle is brought directly to the base of the lower crust. Both are absent in the Alps.

Convective removal of the thermal boundary layer (TBL) could, in theory, explain the Tertiary magmatism. For the following reasons we believe that slab detachment is the more appropriate way to explain the Alpine magmatism. (1) Subduction continued until briefly before the onset of magmatism. Therefore simple homogenous thickening of the lithosphere did not occur. Also, the induced corner flow during subduction may have prevented thickening of the thermal boundary layer. (2) The linear nature of the magmatic belt argues for a linear zone of heated lithosphere, such as required by the narrow rifting model (*Davies and von Blanckenburg*, 1994, Figure 1c). (3) TBL detachment would induce uplift over a large aerial extent. In the

Alps, however, foreland and hinterland basins (molasse) started to form at the time of magmatism.

6.2. Other Models of Alpine Magmatism and Tectonics

One striking feature of the Alpine subduction history is the absence of any volcanic arc or major eroded remnants of pre-Tertiary magmatic activity. This is despite the fact that subduction took place since circa 135 Ma. Various workers have explained the Tertiary Alpine magmatism in terms of subduction melting [e.g., *Gaudemer et al.*, 1988; *Kagami et al.*, 1991; *Waibel*, 1993], but its syncollisional nature makes the slab breakoff model much more probable. One cause for the absence of subduction magmatism may have been the slow pre-Oligocene convergence rates of < 1cm/yr [*Trümpy*, 1980; *Le Pichon et al.*, 1988]. At these velocities the induced asthenospheric corner flow is not sufficiently vigorous to induce melting of the asthenospheric wedge corner [*Davies and Stevenson*, 1992]. Also, the shallow dip, due to either the buoyancy of the oceanic crust and intervening peninsulas or due to the flexural rigidity of a short slab, may have prevented melting [*Davies and Stevenson*, 1992].

The only significant occurrence of volcanic rocks in the Alps are large deposits of andesitic detritus in the Helvetic Tavayannaz Sandstone. These are comparable in age and chemistry to the Periadriatic tonalites [*Fischer and Villa*, 1990; *Waibel*, 1993]. We also explain this volcanism by slab breakoff.

Other models for the magmatism have invoked a general phase of extension in the Oligocene [*Laubscher*, 1983; *Polino et al.*, 1990]. It is interesting that Laubscher mentioned "receding and breaking off of subducted slabs" already. However, contrary to our model he regarded crustal extension above the slab breakoff to have been necessary for the generation of pathways for magma ascent. This idea was inspired by the onset of extensional volcanism surrounding the Alps. However, field studies have shown that the stress field prevailing at crustal levels at the time of the intrusions was compressive [*Schmid*, 1992; *Rosenberg et al.*, 1994]. We believe our model can explain syncompressive melt generation. Extension of the overriding lithosphere following breakoff is possible but not required to partially melt the mantle.

7. Conclusions

The slab breakoff hypothesis presented in this paper supplies a consistent explanation for two of the most controversial aspects of the evolution of the Alps: the Tertiary magmatism and the uplift and exhumation of continental rocks subducted to mantle depths.

Trace element and isotopic compositions of mafic dykes emplaced between 43 and 25 Ma allow the identification of the source which provided the mantle end-members of the Alpine plutons. It is the mechanically stable, chemically enriched lithospheric mantle. The lithospheric melting is consistent with raising the temperature of the 80-km-deep lithospheric base following breakoff at 45 Ma and allowing it to reequilibrate at 30 Ma by continued convergence.

The depth of the melting column at 80 km and the maximum depth to which coesite-bearing crustal rocks have been subducted give the minimum breakoff depth of 100 km. This is the model depth obtained for convergence velocities of 1 cm/yr [*Davies and von Blanckenburg*, 1994], which are typical for the Alps in the Tertiary [*Le Pichon et al.*, 1988].

The decompression of Penninic high-pressure rocks in the Alps, mostly contemporaneous with the onset of igneous activity, is enhanced by the heating and declamping of the crustal lithosphere's rheological layers. This allows their rapid return as buoyant sheets into the crust. Other Alpine features consistent with the breakoff model, of which a thorough discussion is beyond the scope of this paper, are Tertiary regional metamorphism and exhumation of metamorphic basement by both erosion and late extension. As predicted, the magmatism occurs along a narrow linear zone and is confined in time, which makes it distinct from other models of syncollisional magmatism, such as subduction melting, delamination, or thermal boundary layer detachment.

The observations in the Alps, especially the association of magmatic activity and return of subducted rocks, strongly support the theoretical model [*Davies and von Blanckenburg*, 1994]. Similar observations in other mountain belts suggest that this is a common process.

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F. von Blanckenburg, Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, England. (e-mail: fv101@esc.cam.ac.uk)

J. H. Davies, Department of Earth Sciences. University of Liverpool, Brownlow Street, Liverpool L69 3BX, England. (e-mail: davies@liv.ac.uk)

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