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Autor: Blanckenburg, F. von / Kagami, H. / Deutsch, A.

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Dedicated to Prof. Dr. Rudolf H. Steiger on the occasion of his retirement

The origin of Alpine plutons along the Periadriatic Lineament

by *F. von Blanckenburg*[1], *H. Kagami*[2], *A. Deutsch*[3], *F. Oberli*[4], *M. Meier*[4], *M. Wiedenbeck*[5], *S. Barth*[6] and *H. Fischer*[7]

Abstract

Numerous geological, geochemical, and geochronological studies of Oligocene Alpine plutonism have been published over the last ~15 years. In this paper we review the major results of these works, and provide hitherto unpublished Nd–Sr isotope data from mafic dykes and acidic intrusions. Geochemical data require that the source materials of these plutons be mixtures between partial melts from the lithospheric mantle and melted continental crust. Comparisons with simple thermal melting models furthermore indicate that the large amounts of tonalite present in the intrusions resulted from widespread melting of a mafic lower crust induced by a major thermal perturbation. Physical considerations suggest that neither subduction zone melting nor extensional decompression melting were the cause of melt generation. Models based on the loss of the lithospheric mantle root during lithospheric thickening, such as breakoff of subducted oceanic lithosphere, bear the closest similarity to the observations in the Alps. As a result lithospheric weakening by rising melts might have focused deformation into the Periadriatic Lineament, along which the intrusions were emplaced.

Keywords: Alps, Periadriatic Lineament, intrusives, mantle melting, isotope geochemistry, slab breakoff.

1. Introduction

Several Oligocene granitoid intrusions and numerous small basaltic dykes were emplaced along the Periadriatic Lineament, a first order tectonic boundary in the Alps (Fig. 1). The origin of these intrusions has been the subject of prolonged debate. In recent decades numerous models have been proposed for their genesis, including: subduction magmatism (DIETRICH, 1976; TOLLMANN, 1987; KAGAMI et al., 1991), extension-related melting (LAUBSCHER, 1983), melting of the crustal mountain root following convective thinning of the Alpine lithospheric root (DEWEY, 1988), and slab breakoff (VON BLANCKENBURG and DAVIES, 1995, 1996).

Over the last 15 years isotopic studies have yielded important constraints which have focused this debate on those models invoking the mixing of two end member lithologies: basaltic melts produced by partial melting of the Earth's lithospheric mantle, and melted continental crust (e.g. CORTECCI et al. [1979], DEL MORO et al. [1983a], JUTEAU et al. [1986], VAN MARCKE DE LUMMEN and VANDER AUWERA [1990], KAGAMI et al. [1991], VON BLANCKENBURG et al. [1992]). This paper compiles the most significant results of these studies, reports new Sr-Nd-isotopic data from previously unstudied mafic dykes, discusses possible mechanisms for mantle melting, and emphasises the relationship between tectonics and magma emplacement along the Periadriatic Lineament.

[1] Mineralogisch-Petrographisches Institut, Abt. für Isotopengeologie, Universität Bern, Erlachstr. 9a, CH-3012 Bern, Switzerland. <fvb@mpi.unibe.ch>
[2] Graduate School of Science and Technology, Niigata University, Ikarashi 2-cjoume, Niigate 950-21, Japan.
[3] Institut für Planetologie, Wilhelm-Klemm-Str. 10; and Zentrallabor für Geochronologie, Corrensstr. 24, Universität Münster, D-48149 Münster, Germany.
[4] Institut für Isotopengeologie und Mineralische Rohstoffe, ETH-Zentrum, CH-8092 Zürich, Switzerland.
[5] University of New Mexico, 1001 University Blvd, SE, Albuquerque, New Mexico 87106-4342, USA.
[6] Institut für Geologie und Paläontologie, Universität Tübingen, D-72076 Tübingen, Germany.
[7] Vetropac Holding AG, Schützenmattstr. 266, CH-8180 Bülach, Switzerland.

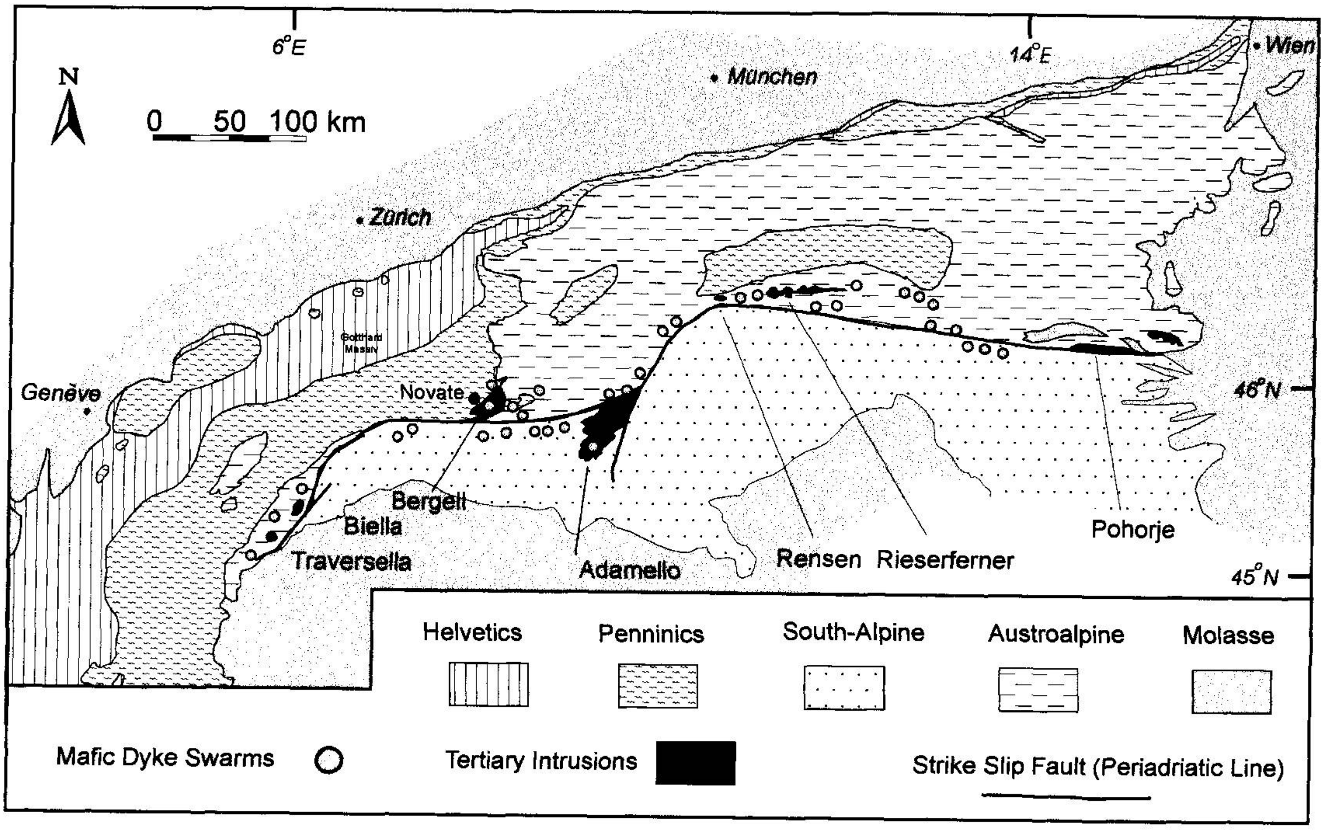

Fig. 1 Tectonic map of the Alps showing the alignment of Tertiary intrusions along the Periadriatic Lineament.

2. Geological setting

The Periadriatic Lineament is the most visible tectonic boundary of the Alps: it divides the Southern Alps from the Austroalpine domain in the Northeast and from the Penninics in the Southwest (Fig. 1). In the Central Alps, this boundary separates the zone of Tertiary metamorphism in the north from the non-metamorphic Southern Alps. Whereas the predominant movement along the Periadriatic Lineament was dextral strike-slip, in the central segment transpressive movements also occurred which led to the exhumation of the Central Alps (SCHMID et al., 1989). This lineament accommodated the anti-clockwise Tertiary rotation of the Adriatic microplate against Europe (COWARD and DIETRICH, 1989).

Along this lineament both large igneous bodies and numerous small acidic dykes were emplaced (EXNER, 1976); small mafic dykes are also common across the area (DAL PIAZ and VENTURELLI, 1983; DEUTSCH, 1984). The timing and origin of these compositionally diverse dykes has been discussed in detail by VON BLANCKENBURG and DAVIES (1995), who concluded that these melts were generated in a region of variably metasomatised lithospheric mantle. This magmatic activity most likely occurred synchronously with the movement along the lineament. The melting regions and emplacement mechanisms of these intrusions are the topic of this paper.

From west to east, the major Periadriatic intrusions are (Fig. 1): Traversella, 28–31 Ma (SCHEURING et al., 1974); Biella, 31 Ma (ROMER et al., 1996); Novate leucogranite, 25 Ma (KÖPPEL and GRÜNENFELDER, 1975); Bergell, 30–32 Ma (VON BLANCKENBURG, 1992, also reviewed by HANSMANN, 1996); Adamello, 38–43 Ma in the southern Re di Castello Massif, 31–35 Ma in the north (DEL MORO et al., 1983b; HANSMANN and OBERLI, 1991); Rensen, 31–32 Ma (BARTH et al., 1989); Rieserferner, 30 Ma (BORSI et al., 1979). The easternmost intrusion is the Bacher, or Pohorje tonalite for which EXNER (1976) assumes a Tertiary age. The geochemistry of this pluton and its associated mafic and andesitic volcanics has been described by ALTHERR et al. (1995). Further ages have been compiled for mafic dykes (VON BLANCKENBURG and DAVIES, 1995), and new ages on acidic dykes have been reported recently (ROMER et al., 1996; SCHÄRER et al., 1996). The intrusion ages of mafic dykes span a wider range from 42 to 24 Ma (DEUTSCH, 1984; VON BLANCKENBURG and DAVIES, 1995), which suggests a protracted episode of melting in the mantle source.

Because most of these intrusions were emplaced into thrusted, and in some places also steepened nappes, they are considered to be typically "post- to syn-collisional". Most of them were emplaced into the Austroalpine nappes, except for the Adamello, which intruded South-Alpine cover and basement, and the Bergell intrusion and the Novate leucogranite which intruded into both the Penninic and Austroalpine domains (BERGER et al., 1996).

3. Geochemistry and Sources of the Periadriatic Magmas

Almost all Periadriatic intrusions belong to the typical gabbro-tonalite-granodiorite-granite calc-alkaline suite. Most of the exposed intrusive area is occupied by tonalite, followed by granodiorite. Gabbros and cumulitic hornblendites are minor lithologies, occurring mainly in the South-Adamello batholith (ULMER et al., 1983; BLUNDY and SPARKS, 1992) and in the Bergell intrusion (DIETHELM, 1985). According to the classification by CHAPPEL and STEPHENS (1988) they can be considered as "I-type" granitoids. The exception is the peraluminous Novate leucogranite, which exhibits an "S-type" character, and which is not the topic of this paper.

The Nd–Sr–O isotopic data are summarised in figures 2 and 3. Published data are complemented by new analyses on whole rock powders from granitoid intrusions and also on mineral separates from mafic dykes (Appendix, Tab. 1, also DEUTSCH, 1984). In general all three isotopic systems imply a mixing between basaltic partial melts originating in the subcontinental lithospheric mantle (ε_{Nd} = +4 to –4, $^{87}Sr/^{86}Sr$ = 0.704 to .708, $\delta^{18}O$ = +6 to +7.5) and melted / assimilated continental crust (ε_{Nd} = –10, $^{87}Sr/^{86}Sr$ = 0.710–0.720, $\delta^{18}O$ = +10); these magma sources and mixing processes have been discussed at length in the literature (CORTECCI et al., 1979; TAYLOR, 1980; DUPUY et al., 1982; JUTEAU et al., 1986; VAN MARCKE DE LUMMEN and VANDER AUWERA, 1990; KAGAMI et al., 1991; VON BLANCKENBURG et al., 1992). One conclusion of these studies is that the lithospheric mantle source is heterogeneous in both its major element and isotopic compositions, leading to variable melt types ranging from calc-alkaline compositions where ε_{Nd} is in most cases +4 to +1, $^{87}Sr/^{86}Sr$ = .704 to .706, and $\delta^{18}O$ = +6 to +7‰, to alkaline and potassic compositions with ε_{Nd} = –2 to –4, $^{87}Sr/^{86}Sr$ = .706 to .720, and $\delta^{18}O \approx$ +7.5‰. Because calc-alkaline rocks with isotopic

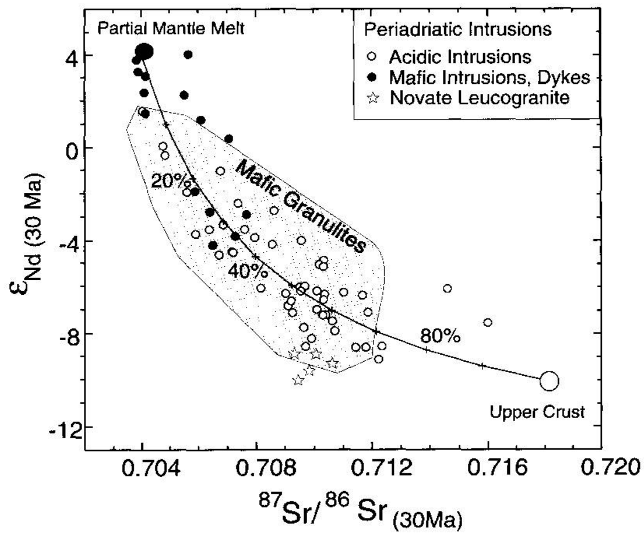

Fig. 2 ε_{Nd} versus $^{87}Sr/^{86}Sr$, time corrected for 30 Ma. The data are compiled from JUTEAU et al. (1986), BARTH et al. (1989), KAGAMI et al. (1991), OSCHIDARI and ZIEGLER (1992), VON BLANCKENBURG et al. (1992), and this study. The field termed "mafic granulites" encompasses mafic to andesitic lower crustal xenoliths from the Eifel and Massif Central (KEMPTON and HARMON, 1992). The mixing line has been calculated for the simple mixing case, using the end member properties of table 4 in VON BLANCKENBURG et al. (1992, Partial mantle melts: $\delta^{18}O$ = +6‰, Sr_{conc} = 170 ppm, $^{87}Sr/^{86}Sr$ = .704, Nd_{conc} = 8.2 ppm, ε_{Nd} = +4; upper crust : $\delta^{18}O$ = +10‰, Sr_{conc} = 100 ppm, $^{87}Sr/^{86}Sr$ = .718, Nd_{conc} = 20 ppm, ε_{Nd} = –10).

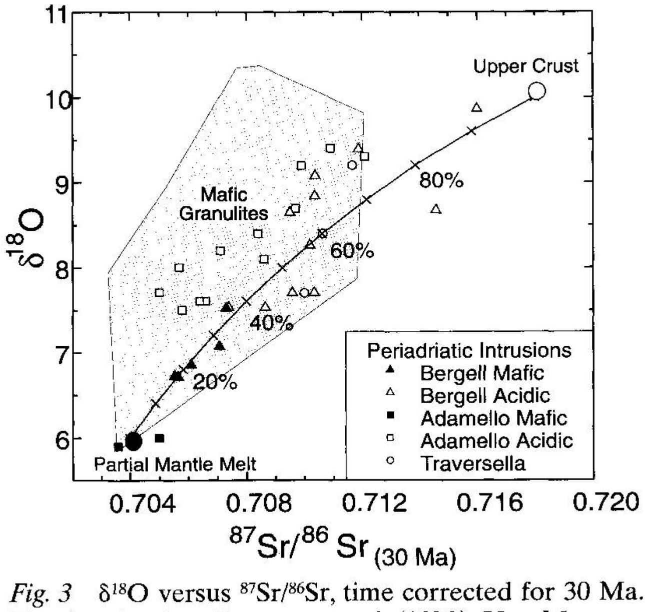

Fig. 3 $\delta^{18}O$ versus $^{87}Sr/^{86}Sr$, time corrected for 30 Ma. The data is after CORTECCI et al. (1979), VAN MARCKE DE LUMMEN and VANDER AUWERA (1990), VON BLANCKENBURG et al. (1992). The field termed "mafic granulites" and the mixing curve are the same as in figure 2.

compositions more akin to the first group are usually found to be the mafic early-differentiates of the felsic intrusions (ULMER et al., 1983; DIETHELM, 1985; KAGAMI et al., 1991; VON BLANCKENBURG et al., 1992), these melts rather than the more alkaline ones are regarded to be the parental melts of the plutons.

If this is the case, then such mixtures of mantle-derived basaltic partial melts and crust contain a larger crustal component than would be predicted solely on thermal arguments. This fact is well illustrated by the simple mixing curves calculated for figures 2 and 3 as based on plausible end member compositions. Excluding late differentiates, the major acidic lithologies require "crustal" contributions of between 10% and 70%; a feature which is particularly apparent in the oxygen isotope system (Fig. 3). Although some scatter might be induced by secondary alteration effects, because the oxygen concentrations of the participating source regions are nearly the same and also because their end member compositions are quite distinct in their ranges, oxygen provides a robust estimate of the mixing proportions.

In contrast, the amount of crust that can be melted by the heat released from crystallising basalt is limited to 35% of the basalt's original mass, assuming an ambient temperature typical of upper crustal levels (SPARKS, 1986). The relationship between temperature and assimilation has been quantified using the simple approach of THOMPSON (1992). The mass ratio (R) between assimilated crust (m_c) and crystallising basalt (m_b), assuming complete heat transfer from magma into the crust, can be calculated from:

$$R = \frac{m_c}{m_b} = \frac{C_b(T_b - T_s) + L_b}{C_c(T_s - T_c) + L_c}$$

where C_c is the mean heat capacity of crustal rocks (circa 1 kJ kg^{-1} K^{-1}), C_b is the mean heat capacity of basalts (1 kJ kg^{-1} K^{-1}), L_b is the latent heat of basalt crystallisation (500 kJ kg^{-1}), L_c is the latent heat of fusion of granitic crust (200 kJ kg^{-1}), T_c is the initial temperature of the crustal basement, T_b is the temperature of the intruding basalt (1250 °C), and T_s is the melting temperature of crust (650 °C for water-saturated granitic crust, 820 °C for dry melting of amphibolite [RUSHMER, 1991]). To make the results compatible with those obtained from isotopic mixing calculations, R was transformed into fraction of crust assimilated by basalt using:

$$x_{crust} = \frac{m_c}{m_c + m_b} = \frac{R}{R+1}.$$

The results, displayed in figure 4, show that ~ 35% of granitic crust and 30% of mafic crust can be assimilated under cold conditions, whereas 50% of granitic crust and 40% of mafic crust can be digested in the case of an initial crustal temperature of 800 °C. Such hot thermal conditions are encountered only in the lower crust; the corresponding high thermal gradients can be achieved in orogenic zones by magmatic underplating of the crust, or even without any magmatic contribution, solely by extension following thickening (ENGLAND and THOMPSON, 1986), provided sufficient time elapsed between thickening and extension to allow for conduction of heat into the crust after thickening.

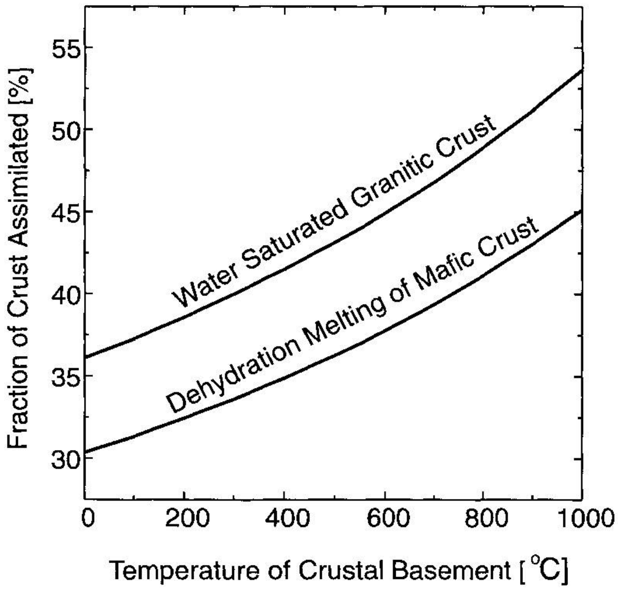

Fig. 4 Fraction of crust that can be assimilated on thermal grounds by basalt intruding into crustal basement at different temperatures. The two curves refer to typical granitic and mafic crustal lithologies. Details of calculations are given in the text.

Based on this line of reasoning we would expect widespread melting of the lower crust. This prediction can be tested using isotopic compositions representative of the lower crust obtained from granulite facies xenoliths brought to the surface by volcanic eruptions. For Central Europe, such data have been published by KEMPTON and HARMON (1992) for xenoliths from volcanic suites from the Eifel and the Massif Central. The Nd–Sr–O isotopic compositions of mafic to andesitic xenoliths from these volcanic centers are represented in figures 2 and 3 by the shaded areas. Note that the vast majority of Periadriatic acidic intrusives falls in these fields. The isotopic compositions of most of the tonalites and granodiorites are therefore compatible with melting of mafic lower crust. Support for this model is given by the broad areal extent of tonalite intrusions. Tonalitic compositions have been generated by partial melting of amphibolites in the laboratory (RUSHMER, 1991). Melting of the lower crust, followed by assimilation and fractional crystallisation (AFC) or magma mixing, have previously been postulated for the Adamello intrusion (DUPUY et al., 1982; KAGAMI et al., 1991).

Thermal calculations (Fig. 4) show that the maximum mass fraction of mafic lower crust which may be assimilated by 1250 °C basalt is 45%. In contrast, the maximum amount implied by isotopic constraints approaches 80–90%. Two possible explanations may resolve this paradox: (a) the observed compositions reflect hybrid mixtures of mantle-derived basalt, mafic lower crust, and acidic upper crust. Generation of large volumes of magma near the mantle/crust transition, mainly by extensive interaction between basaltic melts and the lower crust, has been proposed as a major mechanism for Hercynian magmatism (VOSHAGE et al., 1990); (b) the lower crust was able to melt even without an influx of basalt. This requires very high temperatures for the lower crust. Such temperatures might result from either steepening of the geothermal gradient during lithospheric thickening (ENGLAND and THOMPSON, 1986) or from a higher than normal heat flux across the Moho. The latter possibility will be discussed in the following section.

4. Tectonic models for partial mantle melting

A striking conclusion from the Nd–Sr data is an indisputable origin of the basalts from partial melting of a variably metasomatised lithospheric mantle (ULMER et al., 1983; KAGAMI et al., 1991; VON BLANCKENBURG et al., 1992). This is a surprising result, given that these melts intruded into a thickened lithosphere long after beginning of the continental collision at 55–50 Ma. The geotherms must have been deeply suppressed. Such a situation seems unlikely, yet it has happened in many of the earth's orogenic belts at the same stage of their development. In this section we review the major tectonic models for mantle melting in convergent tectonic settings.

4.1. SUBDUCTION ZONE MELTING

This process has been proposed several times for the Tertiary magmatism (e.g., DIETRICH, 1976; TOLLMANN, 1987; GAUDEMER et al., 1988; KAGAMI et al., 1991). Subduction zone melting at continental margins typically generates the required calc-alkaline parental mantle melts, and, by assimilation of continental crust, large amounts of tonalite. Mantle melting can be induced by the migration of fluids released from the dehydrating slab into the overlying mantle wedge. This effect is shown in the phase diagram shown in figure 5a: at a given geotherm (dashed line), fluid influx would shift the solidus from dry peridotite (DP) to water-saturated (WP), resulting in melting under the P,T conditions denoted by the shaded field. However, numerical modelling by DAVIES and STEVENSON (1992) has shown that the induced asthenospheric wedge flow (lines with arrows in the cartoon of Fig. 5a) has to be vigorous enough to prevent the freezing in of hydrous melts as amphibole peridotite. Subduction velocities of 6 ± 2 cm a^{-1} are required (DAVIES and STEVENSON, 1992). The convergence velocity in the Tertiary Alps has been estimated at 0.3–1.5 cm a^{-1} (SCHMID et al., 1996). Tertiary Alpine subduction was apparently too slow to induce melting in the asthenospheric wedge. Alternatively, a shallow dip, due to intervening peninsulas (e.g., the Briançonnais), could have prevented melting. The lack of subduction induced magmatism is consistent with the absence of any volcanic arc in the Cretaceous or early Tertiary Alps. Oligocene volcanism, of which remnants are preserved in the Helvetic Taveyannaz Sandstone, was both contemporaneous and similar in isotopic composition to the Periadriatic plutonism, suggesting they may be the product of the same mechanism (FISCHER and VILLA, 1990; RUFFINI et al., 1997).

Recently, the *in situ* melting of deeply subducted continental rocks has been proposed as a mechanism for the generation of Periadriatic plutons (DUCHÊNE et al., 1997). It was argued that the similarity between the Nd isotope compositions of subducted felsic rocks and that of the Periadriatic plutons, and the contemporaneity of the intrusions with high pressure metamorphism make melting of these eclogite facies rocks a likely source for the magmatism. We regard the extraction of the required tonalitic and granitic melt volumes from within mantle depths of 100 km to their emplacement positions without further modification as a physically difficult process. The partial melting of lithospheric mantle, followed by intra-crustal melting as described above is a more likely explanation for the plutonism.

4.2. LITHOSPHERIC EXTENSION

Inspired by the onset of extension in graben systems surrounding the Alps, LAUBSCHER (1983, 1988) brought forward the idea of lithospheric extension as a cause for Periadriatic magmatism. He assumed a "back-arc spreading" regime for the

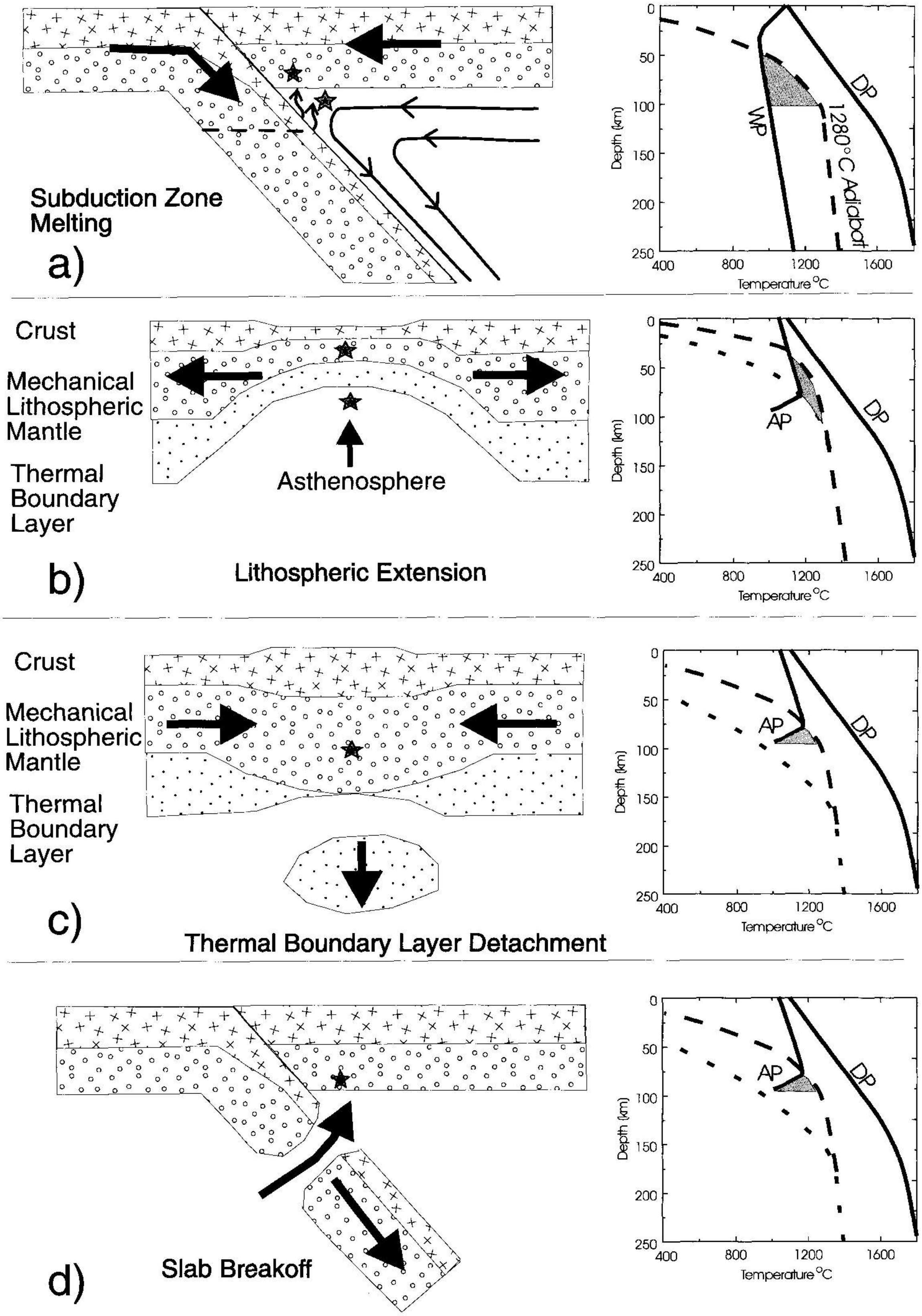

Fig. 5 a–d) Tectonic scenarios leading to mantle melting. Regions potentially undergoing partial melting are marked by stars. On the right, phase diagrams for peridotite show PT conditions for melting. *DP* is the dry peridotite solidus (McKenzie and Bickle, 1988), *WP* is the water-saturated peridotite solidus (Green, 1973), and *AP* is the amphibole peridotite solidus (Mengel and Green, 1989). Initial geotherms are short-dashed lines; the geotherms following the tectonic event are long-dashed. The shaded areas show the regions where the respective solidi are overstepped and partial melting can occur.

whole Alps, where "the mere fact of the intrusions suggests an extensional scenario at that time" (LAUBSCHER, 1988). Extension melting of the mantle is an attractive hypothesis for post-collisional magmatism, as both the asthenospheric mantle and the lithospheric mantle may melt. Furthermore, the upwelling of hot mantle material would generate a strong thermal perturbation which might induce the observed crustal melting. The effects which extension would have on mantle melting are shown in figure 5b. Lithospheric thinning will lead to an upwelling of asthenospheric mantle. At a potential mantle temperature of 1280 °C, typically assumed for the mantle below the continents at ca. 100 km depth, the dry peridotite solidus (DP) would be transected only if thinning leads to an upwelling of the asthenosphere to a depth of less than 50 km (MCKENZIE and BICKLE, 1988). In such a case the asthenospheric mantle would melt, leading to MORB-like isotopic compositions in the resulting magma. For the Periadriatic zone this model can be ruled out due to the observed isotopic compositions which require the extensive involvement of an enriched lithospheric mantle.

Because enriched lithospheric mantle has a lower solidus where OH-bearing minerals are present (e.g., amphibole, phlogopite), the melting of lithospheric mantle could occur even with less extension than required to melt dry peridotite (note the amphibole peridotite solidus [AP] in Fig. 5b). In such a case the upward displacement of the geotherm (short-dashed to long-dashed) would lead to melting within the PT conditions indicated by the shaded field. However, for geological reasons this extension model appears unlikely: the intrusion, at least both of the Bergell pluton and of the small plutonic bodies north of the Adamello pluton (MARTIN et al., 1993) occurred during a compressive tectonic stage (ROSENBERG et al., 1995; BERGER et al., 1996; SCHMID et al., 1996). Extension in other basement sections of the Alps post-dates the intrusions (SELVERSTONE, 1988; RATSCHBACHER et al., 1991; MANCKTELOW, 1992; STECK and HUNZIKER, 1994). In the hypothetical case that a (yet unrecognised) phase of extension took place at 40–30 Ma, lithospheric thinning would have post-dated continental collision: geotherms would have been suppressed during compression, and, given the short time elapsed between thickening and hypothetical extension, the subsequent extension would only have restored them towards their initial gradients. Thus, such post-thickening extension would most probably not lead to mantle melting.

4.3. THERMAL BOUNDARY LAYER DETACHMENT

DEWEY (1988) and DAL PIAZ and GOSSO (1993) proposed this model as the mechanism for generating the Adamello and Bergell plutons. Thermal boundary layer detachment is a mechanism by which syn- to post-collisional magmatism of both mantle and crustal origin can be produced during continental thickening. The thermal boundary layer (TBL) is the mantle region underlying the mechanically stable lithospheric mantle, where heat transport is dominated by convection, as in the underlying asthenosphere below, rather than by conduction, as in the overlying lithosphere. During continental collision the lithosphere will thicken, thereby pressing the cold, dense lithospheric root deep into the asthenospheric mantle. Due to its higher density, the TBL would become unstable, and would be displaced convectively into the asthenospheric mantle (Fig. 5c). The hot asthenospheric mantle replacing it would heat the lithosphere, thereby leading to the melting of the mantle lithosphere (HOUSEMAN et al., 1981). The magmatic consequences of TBL detachment have been reviewed by TURNER et al. (1992). TBL detachment could well be the explanation for the Alpine mantle melting. However, it would lead to more widespread melting than the localised area of the Periadriatic Lineament. Detachment might also lead to plateau uplift (ENGLAND and HOUSEMAN, 1988), whereas in the Alps both the Molasse and Po Basins were formed at the time of the intrusions. Most importantly, subduction of continental crust had continued until only briefly before the emplacement of the Periadriatic intrusions, as witnessed by the Oligocene ultra-high-pressure metamorphism in the Alps. A homogeneous thickening on the lithospheric scale as required for TBL detachment is not obvious from the geological record.

4.4. SLAB BREAKOFF

This process has been proposed as an explanation for Alpine lithospheric mantle melting with the concomitant or slightly earlier uplift of high-pressure facies rocks (VON BLANCKENBURG and DAVIES, 1995, 1996). Slab breakoff, the detachment of subducted oceanic lithosphere from continental lithosphere during continental collision, will result in post-collisional mantle magmatism similar to the TBL detachment case. This model has the added advantage of taking into account the fact that active subduction of continental lithosphere continued until briefly before the onset of magmatism. The proposed mechanism can be summarised as follows: subsequent to the closure of an oceanic basin, when light continental lithosphere tries to follow dense oceanic lithosphere into the subduction zone, the change in buoyancy forces may lead to the detachment of the downgoing oceanic slab from the more buoyant continental slab. The rifting within the slab will bring hot asthenospheric mantle directly into contact with the lithosphere of the overriding plate, which becomes heated by the asthenospheric flow induced by the sinking oceanic slab (Fig. 5d). The magmatic consequences are similar to those in the TBL detachment case, but they will be more localised and more instantaneous following the detachment (DAVIES and VON BLANCKENBURG, 1995). Breakoff may release crustal layers from the dead-weight of the associated oceanic lithosphere, thereby allowing for a rapid return into the crust of these high-pressure metamorphic rocks. The continuing asthenospheric flow at the base of the lithosphere will also result in the conductive heating of the lower crust, which might induce lower crustal melting as discussed in the previous section. The localised nature of mantle melting above the breakoff point would result in a linear trace of igneous activity when observed in two dimensions – similar to the observed pattern along the Periadriatic Lineament.

5. Emplacement of intrusions along the Periadriatic Lineament

The major remaining question concerns the emplacement mechanism of the intrusions. Why are all intrusions aligned along the Periadriatic Lineament? This is of particular interest as SCHMID et al. (1996) argued recently that a precursor to the Periadriatic Lineament has been in existence since the Cretaceous. An alternative interpretation would be as follows: the slab breakoff mechanism, once initiated, would rapidly propagate laterally (YOSHIOKA and WORTEL, 1995). This explains the nearly simultaneous peak in magmatic activity along ~ 1000 km strike. As explained above, it will generate a linear trace of magmatic activity and also of thermal weakening of the lithosphere. The strong temperature dependence of lithospheric rheology implies that above the breakoff trace the lithosphere will strain weaken, by heat conduction and heat advection through uprising melts (SANDIFORD et al., 1992). For example, intrusion of a mafic magma sill with a thickness of 3 km at the Moho into lithosphere with surface heat flow of 65 mW m^{-2}, followed by granite genesis at 10 km depth and 800 °C will lead to an increase in strain rate from ca. 1×10^{-16} s^{-1} to ca. 3×10^{-14} s^{-1} (SANDIFORD et al., 1992). Thus, sufficient thermal weakening would be provided to localise deformation during convergence. The region along the breakoff trace therefore is favoured to form a tectonic lineament. In the case of the Periadriatic Line, the lineament accommodated backfolding in the Central Alps, followed by a dextral displacement during the anticlockwise rotation of Adria microplate against Europe during ongoing, probably oblique, convergence. This led to several hundred km of strike slip movement, and transpressive movements at the bend of the line south of the Central Alps (SCHMID et al., 1989).

The situation may have partially resembled that of the present-day Sumatra Arc where oblique subduction is accommodated by a distinct compressive component normal to the arc and a second, distinct strike slip motion parallel to the arc; the strike slip fault is where volcanic activity is focused (FITCH, 1972). In the case of the Alps, plutonism occurred in the Oligocene. The volcanic (andesitic) debris of the Taveyannaz Sandstone, similar in age and isotopic composition (VUAGNAT, 1983; FISCHER and VILLA, 1990; RUFFINI et al., 1997) hints at some limited volcanism that was very likely related to the same process.

Concerning the Periadriatic plutons themselves, it is now known and accepted that their emplacement took place in a syn-compressive environment. Structural studies in the Bergell intrusion have shown that this pluton was emplaced into a compressive environment (ROSENBERG et al., 1994; BERGER et al., 1996). It has been shown that plutonism can occur in compressive environments, such that extension is not required for their emplacement (HOLLISTER and CRAWFORD, 1986; HUTTON, 1988). In fact compression and strike slip faulting appears to facilitate segregation and movement of melts. Furthermore, the presence of melts appears to enhance strike slip faulting and exhumation of basement rocks (HOLLISTER, 1993).

Finally it must be noted that the model we have described for the Oligocene Alps, in particular the magmatism, may also apply further east in the Pannonian Basin and the Carpathian Arc. Ages of Carpathian volcanic and metamorphic rocks decrease along the arc away from the Alps (PÉCSKAY et al., 1995) This observation is compatible with the concept of slab breakoff propagating along the Arc (PERESSON and DECKER, 1997). Similar lateral propagation of slab breakoff was inferred for the Apennines, starting in the late Miocene and continuing throughout the Mediterranean area up to the Quarternary (WORTEL and SPAKMAN, 1992).

6. Conclusions

The principal conclusions of this review are:

1) Based on geochemical and isotopic data, the Oligocene Periadriatic intrusions were formed from basaltic partial melts, originating in the lithospheric mantle, mixing with magmas generated from both lower as well as upper continental crust.

2) The amounts of assimilated crust, as estimated by isotopic mixing calculations (20–70%), are in excess of what can actually be melted by crystallising basalt at upper crustal temperatures. It is thus required that melting of lower crust at temperatures of ca. 800 to 1000 °C took place. The tonalites and granodiorites include a large proportion of melted mafic lower crust.

3) Several of the scenarios proposed in the literature relating magma genesis to a specific tectonic process cannot be applied to the Periadriatic intrusions. For subduction zone melting the convergence velocities were too low. Lithospheric extension probably did not take place, and even if so, it would not have led to mantle melting following lithospheric thickening. Convective removal of a thickened thermal boundary layer could explain the magmatism, but not its localised nature. Such a mechanism is also less likely because continental subduction acted until only briefly before the onset of the igneous activity. Separation of the subducted continental lithosphere from the preceding oceanic lithosphere via slab breakoff, on the other hand, would lead to linearly aligned intrusions, and might well explain the concurrent uplift of high-pressure metamorphosed continental crust.

4) Weakening of the crust by the emplacement of melts in the lithosphere facilitated the ascent of melts along the Periadriatic Lineament, in a strike-slip or transpressive environment.

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References

ALTHERR, R., LUGOVIC, B., MEYER, H.P. and MAJER, V. (1995): Early Miocene post-collisional calc-alkaline magmatism along the easternmost segment of the Periadriatic fault system (Slovenia and Croatia). Mineral. Petrol. 54, 225–247.

BARTH, S., OBERLI, F. and MEIER, M. (1989): U–Th–Pb systematics of morphologically characterized zircon and allanite: a high-resolution isotopic study of the Alpine Rensen pluton (northern Italy). Earth Planet. Sci. Lett. 95, 235–254.

BERGER, A., ROSENBERG, C. and SCHMID, S.M. (1996): Ascent, emplacement and exhumation of the Bergell pluton within the Southern Steep Belt of the Central Alps. Schweiz. Mineral. Petrogr. Mitt. 76, 357–382.

BLUNDY, J.D. and SPARKS, R.S.J. (1992): Petrogenesis of mafic inclusions in granitoids of the Adamello Massif, Italy. J. Petrol. 33, 1039–1104.

BORSI, S., DEL MORO, A., SASSI, F.P. and ZIRPOLI, G. (1979): On the age of Vedrette di Ries (Rieserferner) massif and its geodynamic significance. Geol. Rundsch. 68, 41–60.

CHAPPEL, B.W. and STEPHENS, W.E. (1988): Origin of infracrustal (I-type) granite magmas. Trans. Royal Soc. Edinburgh: Earth Sciences 79, 71–86.

CORTECCI, G., DEL MORO, A., LEONE, G. and PARDINI, G.C. (1979): Correlation between strontium and oxygen isotopic compositions of rocks from the Adamello Massif (Northern Italy). Contrib. Mineral. Petrol. 68, 421–427.

COWARD, M. and DIETRICH, D. (1989): Alpine tectonics – an overview. In: COWARD, M.P., DIETRICH, D. and PARK, R.G. (eds): Alpine Tectonics. Geological Society Special Publication, vol. 45, London, 1–29.

DAL PIAZ, G.V. and GOSSO, G. (1993): Some remarks on evolution of the Alpine lithosphere. Quaderni di Geodinamica Alpina e Quaternaria 2, 93–101.

DAL PIAZ, G.V. and VENTURELLI, G. (1983): Brevi riflessioni sul magmatismo post-ofiolitico nel quadro dell'evoluzione spazio-temporale delle Alpi. Mem. Soc. Geol. Ital. 26, 5–19.

DAVIES, J.H. and STEVENSON, D.J. (1992): Physical model of source region of subduction zone volcanics. J. Geophys. Res. 97, 2037–2070.

DAVIES, J.H. and VON BLANCKENBURG, F. (1995): Slab breakoff: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. Earth Planet. Sci. Lett. 129, 85–102.

DEL MORO, A., FERRARA, G., TONARINI, S. and CALLEGARI, E. (1983a): Rb–Sr systematics on rocks from the Adamello batholith (Southern Alps). Mem. Soc. Geol. Ital. 26, 261–284.

DEL MORO, A., PARDINI, G., QUERCIOLI, C., VILLA, I.M. and CALLEGARI, E. (1983b): Rb/Sr and K/Ar chronology of Adamello granitoids, Southern Alps. Mem. Soc. Geol. Ital. 26, 285–299.

DEUTSCH, A. (1984): Young Alpine dykes south of the Tauern Window (Austria): a K–Ar and Sr isotope study. Contrib. Mineral. Petrol. 85, 45–57.

DEUTSCH, A., BUHL, D. and LANGENHORST, F. (1992): On the significance of crater ages – new ages for Dellen (Sweden) and Araguainha (Brazil). Tectonophysics 216, 205–218.

DEWEY, J.F. (1988): Extensional collaps of orogens. Tectonics 7, 1123–1139.

DIETHELM, K. (1985): Hornblendite und Gabbros im östlichen Bergell (Val Sissone, Provinz Sondrio, Italien). Schweiz. Mineral. Petrogr. Mitt. 65, 223–246.

DIETRICH, V.J. (1976): Plattentektonik in den Ostalpen. Eine Arbeitshypothese. Geotekt. Forsch. 50, 1–84.

DUCHÊNE, S., BLICHERT-TOFT, J., LUAIS, B., TÉLOUK, P., LARDEAUX, J.M. and ALBARÈDE, F. (1997): The Lu–Hf dating of garnets and the ages of the Alpine high-pressure metamorphism. Nature 387, 586–588.

DUPUY, C., DOSTAL, J. and FRATTA, M. (1982): Geochemistry of the Adamello Massif (Northern Italy). Contrib. Mineral. Petrol. 80, 41–48.

ENGLAND, P.C. and HOUSEMAN, G.A. (1988): The mechanics of the Tibetan Plateau. Phil. Trans. Royal Soc. London A 326, 301–320.

ENGLAND, P.C. and THOMPSON, A. (1986): Some thermal and tectonic models for crustal melting in continental collision zones. In: COWARD, M.P. and RIES, A.C. (eds): Collision Tectonics. Geol. Soc. Special Publication, vol. 19, London, 83–94.

EXNER, C. (1976): Die geologische Position der Magmatite des periadriatischen Lineamentes. Verh. Geol. B.-A. Wien 2, 3–64.

FISCHER, H. and VILLA, I.M. (1990): Erste K/Ar- und $^{40}Ar/^{39}Ar$-Hornblende-Mineralalter des Taveyannaz-Sandsteins. Schweiz. Mineral. Petrogr. Mitt. 70, 73–75.

FITCH, T.J. (1972): Plate convergence, transcurrent faults, and internal deformation adjacent to Southeast Asia and the Western Pacific. J. Geophys. Res. 77, 4432–4460.

GAUDEMER, Y., JAUPART, C. and TAPPONNIER, P. (1988): Thermal control on post-orogenic extension in collision belts. Earth Planet. Sci. Lett. 89, 48–62.

GREEN, D.H. (1973): Experimental melting studies on a model upper mantle composition at high pressure under water-saturated and water-undersaturated conditions. Earth Planet. Sci. Lett. 19, 37–53.

HANSMANN, W. (1996): Age determinations on the Tertiary Masino-Bregaglia (Bergell) intrusives (Italy, Switzerland): a review. Schweiz. Mineral. Petrogr. Mitt. 76, 421–451.

HANSMANN, W. and OBERLI, F. (1991): Zircon inheritance in an igneous rock suite: Implications for the petrogenesis of the southern Adamello batholith (Italian Alps). Contrib. Mineral. Petrol. 107, 501–518.

HOLLISTER, L.S. (1993): The role of melt in the uplift and exhumation of orogenic belts. Chem. Geol. 108, 31–48.

HOLLISTER, L.S. and CRAWFORD, M.L. (1986): Melt-enhanced deformation: A major tectonic process. Geology 14, 558–561.

HOUSEMAN, G.A., MCKENZIE, D.P. and MOLNAR, P. (1981): Convective instability of a thickened boundary layer and its relevance for the thermal evolution of continental convergent belts. J. Geophys. Res. 86, 6115–6132.

HUTTON, D.H.W. (1988): Granite emplacement mechanisms and tectonic controls: inferences from deformation studies. Trans. Royal Soc. Edinburgh: Earth Sciences 79, 245–255.

JUTEAU, M., MICHARD, A. and ALBARÈDE, F. (1986): The Pb–Sr–Nd isotope geochemistry of some recent circum-Mediterranean granites. Contrib. Mineral. Petrol. 92, 331–340.

KAGAMI, H., ULMER, P., HANSMANN, W., DIETRICH, V. and STEIGER, R.H. (1991): Nd–Sr isotopic and geochemical characteristics of the southern Adamello (northern Italy) intrusives: implications for crustal versus mantle origin. J. Geophys. Res. 96, 14331–14346.

KEMPTON, P.D. and HARMON, R.S. (1992): Oxygen isotope evidence for large-scale hybridization of the lower crust during magmatic underplating. Geochim. Cosmochim. Acta 56, 971–986.

KÖPPEL, V. and GRÜNENFELDER, M. (1975): Concordant U–Pb ages of monazite and xenotime from the Central Alps and the timing of the high temperature Alpine metamorphism, a preliminary report. Schweiz. Mineral. Petrogr. Mitt. 55, 129–132.

LAUBSCHER, H.P. (1983): The late Alpine (Periadriatic) intrusions and the Insubric Line. Mem. Soc. Geol. Ital. 26, 21–30.

LAUBSCHER, H. (1988): Material balance in Alpine orogeny. Geol. Soc. Am. Bull. 100, 1313–1328.

MANCKTELOW, N.S. (1992): Neogene lateral extension during convergence in the Central Alps: Evidence from interrelated faulting and backfolding around the Simplonpass (Switzerland). Tectonophysics 215, 295–317.

MARTIN, S., PROSSER, G. and MORTEN, L. (1993): Tectono-magmatic evolution of sheeted plutonic bodies along the North Giudicare line (northern Italy). Geol. Rundsch. 82, 51–66.

MCKENZIE, D. and BICKLE, M.J. (1988): The volume and composition of melt generated by extension of the lithosphere. J. Petrol. 29, 625–679.

MENGEL, K. and GREEN, D.H. (1989): Stability of amphibole and phlogopite in metasomatized peridotite under water-saturated and water-undersaturated conditions. In: ROSS, J. (ed.): Kimberlites and related rocks. Vol. 14. Geol. Soc. of Australia Special Publication, Oxford, 571–581.

OSCHIDARI, H. and ZIEGLER, U.R.F. (1992): Vergleichende Sm-Nd- und Rb-Sr-Untersuchungen an Bergeller Geröllen aus der Gonfolite Lombarda ("Südalpine Molasse") und an Bergeller und Novate-Granitoiden des Ursprungsgebietes. Eclogae geol. Helv. 85, 375–384.

PÉCSKAY, Z., LEXA, J., SZAKACS, A., BALOGH, K., SEGHEDI, I., KONECNY, V., KOVACS, M., MARTON, E., KALICIAK, M., SZEKY-FUX, V., POKA, T., GYARMATI, P., EDELSTEIN, O., ROSU, E. and ZEC, B. (1995): Space and time distribution of Neogene-Quaternary volcanism in the Carpatho-Pannonian region. Acta Vulcanol. 7, 15–28.

PERESSON, H. and DECKER, K. (1997): Far-field effects of late Miocene subduction in the Eastern Carpathians: E–W compression and inversion of structures in the Alpine-Carpathian-Pannonion region. Tectonics 16, 38–56.

RATSCHBACHER, L., FRISCH, W., LINZER, H.G. and MERLE, O. (1991): Lateral extrusion in the Eastern Alps, Part 2: structural analysis. Tectonics 10, 257–271.

ROMER, R.L., SCHÄRER, U. and STECK, A. (1996): Alpine and pre-Alpine magmatism in the root-zone of the western Central Alps. Contrib. Mineral. Petrol. 123, 138–158.

ROSENBERG, C., BERGER, A., DAVIDSON, C. and SCHMID, S.M. (1994): Messa in posto del plutone do Masino-Bregaglia, Alpi Centrali / Emplacement of the Masino-Bregaglia (Bergell) Pluton, Central Alps. Atti Ticinesi Sci. Terra Ser. Spec. 1, 31–39.

ROSENBERG, C., BERGER, A. and SCHMID, S.M. (1995): Observations from the floor of a granitoid pluton: a constraint on the driving force of final emplacement. Geology 23, 443–446.

RUFFINI, R., POLINO, R., CALLEGARI, E., HUNZIKER, J.C. and PFEIFER, H.R. (1997): Volcanic clast-rich turbidites of the Taveyanne sandstones from the Thônes syncline (Savoie, France): records for a Tertiary postcollisional volcanism. Schweiz. Mineral. Petrogr. Mitt. 77, 161–174.

RUSHMER, T. (1991): Partial melting of two amphibolites: contrasting experimental results under fluid-absent conditions. Contrib. Mineral. Petrol. 107, 41–59.

SANDIFORD, M., FODEN, J., ZHOU, S. and TURNER, S. (1992): Granite genesis and the mechanics of convergent orogenic belts with application to the southern Adelaide Fold Belt. Trans. Royal Soc. Edinburgh: Earth Sciences 83, 83–93.

SCHÄRER, U., COSCA, M., STECK, A. and HUNZIKER, J. (1996): Termination of major ductile strike-slip shear and differential cooling along the Insubric Line (Central Alps): U–Pb, Rb–Sr and $^{40}Ar/^{39}Ar$ ages of cross-cutting pegmatites. Earth Planet. Sci. Lett. 142, 331–351.

SCHEURING, B., AHRENDT, H., HUNZIKER, J.C. and ZINGG, A. (1974): Palaeobotanical and geochronological evidence for the Alpine age of the metamorphism in the Sesia-Zone. Geol. Rundsch. 63, 305–326.

SCHMID, S.M., AEBLI, H.R., HELLER, F. and ZINGG, A. (1989): The role of the Periadriatic Line in the tectonic evolution of the Alps. In: COWARD, M.P., DIETRICH, D. and PARK, R.G. (eds): Alpine Tectonics. Geol. Soc. Spec. Publ., vol. 45, London, 153–171.

SCHMID, S.M., PFIFFNER, O.A., FROITZHEIM, N., SCHÖNBORN, G. and KISSLING, E. (1996): Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. Tectonics 15, 1036–1064.

SELVERSTONE, J. (1988): Evidence for east-west crustal extension in the Eastern Alps: Implications for the unroofing history of the Tauern Window. Tectonics 7, 87–105.

SPARKS, R.S.J. (1986): The role of crustal contamination in magma evolution through geological time. Earth Planet. Sci. Lett. 78, 211–223.

STECK, A. and HUNZIKER, J. (1994): The Tertiary structural and thermal evolution of the central Alps – compressional and extensional structures in an orogenic belt. Tectonophysics 238, 229–254.

TAYLOR, H.P. (1980): The effects of assimilation of country rocks by magmas on $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ systematics in igneous rocks. Earth Planet. Sci. Lett. 47, 243–254.

THOMPSON, A.B. (1992): Metamorphism and Fluids. In: BROWN, G., HAWKESWORTH, C. and WILSON, C. (eds): Understanding the Earth. Cambridge University Press, Cambridge, 222–250.

TOLLMANN, A. (1987): The Alpidic evolution of the Eastern Alps. In: FLÜGEL, H.W. and FAUPL, P. (eds): Geodynamics of the Eastern Alps. Deuticke, Vienna, 361–378.

TURNER, S., SANDIFORD, M. and FODEN, J. (1992): Some geodynamic and compositional constraints on "postorogenic" magmatism. Geology 20, 931–934.

ULMER, P., CALLEGARI, E. and SONDEREGGER, U.C. (1983): Genesis of the mafic and ultramafic rocks and their genetical relations to the tonalitic-trondhjemitic granitoids of the southern part of the Adamello batholith (Northern Italy). Mem. Soc. Geol. Ital. 26, 171–222.

VAN MARCKE DE LUMMEN, G. and VANDER AUWERA, J. (1990): Petrogenesis of the Traversella diorite (Piemonte, Italy). Lithos 24, 121–136.

VON BLANCKENBURG, F. (1992): Combined high-precision chronometry and geochemical tracing using accessory minerals: applied to the Central-Alpine Bergell intrusion (central Europe). Chem. Geology 100, 19–40.

VON BLANCKENBURG, F. and DAVIES, J.H. (1995): Slab breakoff: A model for syncollisional magmatism and tectonics in the Alps. Tectonics 14, 120–131.

VON BLANCKENBURG, F. and DAVIES, J.H. (1996): Feasibility of double slab breakoff (Cretaceous and Tertiary) during the Alpine convergence. Eclogae geol. Helv. 89, 111–127.

VON BLANCKENBURG, F., FRÜH-GREEN, G., DIETHELM, K. and STILLE, P. (1992): Nd-, Sr-, O-isotopic and chemical evidence for a two-stage contamination history of mantle magma in the Central-Alpine Bergell intrusion. Contrib. Mineral. Petrol. 110, 33–45.

VOSHAGE, H., HOFMANN, A.W., MAZZUCCHELLI, M., RIVALENTI, G., SINIGOI, S., RACZEK, I. and DEMARCHI, G. (1990): Isotopic evidence from the Ivrea Zone for a hybrid lower crust formed by magmatic underplating. Nature 347, 731–736.

VUAGNAT, M. (1983): Les grès de Taveyanne et roches similaires: vestiges d'une activité magmatique Tardi-Alpine. Mem. Soc. Geol. Ital. 26, 39–53.

WORTEL, M.J.R. and SPAKMAN, W. (1992): Structure and dynamics of subducted lithosphere in the Mediterranean region. Proc. Kon. Ned. Akad. v. Wetensch. 95, 325–347.

YOSHIOKA, S. and WORTEL, M.J.R. (1995): Three-dimensional numerical modeling of detachment of subducted lithosphere. J. Geophys. Res. 100, 20223–20244.

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Appendix

Tab. 1 New Sr and Nd isotopic data on some intrusions and mafic dykes.

Sample	Rb	Sr	Sm	Nd	$^{87}Rb/^{86}Sr$	$^{147}Sm/^{144}Nd$	$^{87}Sr/^{86}Sr$ Meas	$^{87}Sr/^{86}Sr$ 30 Ma	$^{143}Nd/^{144}Nd$ Meas	ε_{Nd} 30 Ma
		[ppm]								
Intrusions[1]										
Traversella Diorite	128.2	731.2	8.876	49.38	.5075	.1087	.71088	.71066	.512189	−7.82
Biella Syenite	300.2	979.7	8.544	43.89	.8867	.1177	.70937	.70899	.512262	−6.43
Novate Leucogranite	111.1	549.2	2.591	12.96	.5854	.1208	.71002	.70977	.512156	−8.57
Bergell Granodiorite	156.4	456.0	5.844	33.22	.9841	.1064	.71077	.71035	.512256	−6.51
Bergell Tonalite LC09	104.7	387.3	7.457	42.73	.7826	.1055	.71117	.71084	.512269	−6.24
Bergell Tonalite LC01	88.37	265.3	4.284	20.73	.9642	.1249	.71197	.71156	.512273	−6.24
Rieserferner Granite	138.3	361.8	4.015	19.79	1.106	.1226	.71056	.71051	.512275	−6.20
Pohorje Tonalite	113.4	514.3	5.134	34.12	.6378	.0910	.70708	.70681	.512534	−1.03
Hornblendes from Mafic Dykes[2]										
Ga-5 (Calc-Alkaline)	7.578	93.01	27.13	105.0	.2355	.1563	.706613	.706512	.512420	−4.09
Ga-23 (Shoshonite)	10.25	520.4	11.96	54.18	.05694	.1336	.707762	.707737	.512473	−2.97
D 42 (Alkalibasalt)	12.02	1285	16.60	87.95	.02704	.1142	.705678	.705666	.512524	−1.92
D 52 (Alkalibasalt)	7.447	808.6	11.68	56.51	.02662	.1250	.706304	.706293	.512485	−2.70

(1) Analysed by H. Kagami and H. Fischer. Analytical methods are essentially those of KAGAMI et al. (1991). ε_{Nd} has been calculated using $^{143}Nd/^{144}Nd_{CHUR}$ = .512638.
(2) Analysed by A. Deutsch. Mafic Dykes have been described in DEUTSCH (1984). 8 to 21 mg of primary hornblendes have been hand separated from dykes. Analytical techniques are as in DEUTSCH et al. (1992).

Sample locations
Traversella: Creek above Pastore
Biella: Giuseppe Gamma; Quarry above Santuario
Novate: Quarry at Road in Novate
Bergell Granodiorite: Landslide above Point 1767 along path from Bagni del Masino to Rifugio Omio, Swiss Grid Coordinates 165.05 / 124.35
Bergell Tonalite LC01: Fresh road cut between Church of San Giovanni and the village of Bioggio, Swiss Grid Coordinates: 761.24 / 114.78
Bergell Tonalite LC09: Quarry north of sporting fish pond in Mera Valley. Swiss Grid Coordinates 754.4 / 115.7
Rieserferner: Quarry inbetween Erlsbach and Patscher Alm, Defereggental, ca. 250 m above Pt. 1644
Pohorje: Ribnica na Pohorju, 2 km above Josipdol, Ing Mag Pohorje Quarry No. 5

Locations of mafic dykes are as in DEUTSCH (1984)