The record of Periadriatic volcanism in the Eastern Alpine Molasse zone and its palaeogeographic implications

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ABSTRACT

Precise provenance analysis of andesite and dacite pebbles from conglomerates in the Eastern Alpine Molasse zone, using geochemical and geochronological methods, provides evidence for a synorogenic volcanic chain in the Eastern Alps which is completely eroded today. This volcanism was related to Periadriatic magmatism along the Periadriatic lineament and took place in the Palaeogene, roughly between 40 and 30 Ma. The occurrence of remnants of these volcanic rocks together with other marker lithologies in the Eastern Alpine Molasse, implies an early to middle Miocene drainage system which was, in some respects, similar to the present Inn river system, but had a considerably larger catchment area, reaching farther south. The Palaeo-Inn drained the central and eastern sections of the Periadriatic magmatic belt to the northern foreland basin.

Terra Nova, 12, 42–47, 2000

Introduction

The sedimentary record in foreland basins at the immediate front of an orogenic wedge provides an important terrain for geodynamic and geomorphological studies (Frisch *et al*., 1998). The Eastern Alpine Molasse zone comprises a number of Miocene alluvial fans which reveal information about the erosional and tectonic denudation of the Eastern Alps (Fig. 1).

Pebbles of retrograde eclogites, pseudotachylytes, serpentinites and certain types of gneisses provide useful information about the identity of their source areas (Brügel, 1998). Some of the most significant marker lithologies are undeformed and unmetamorphosed volcanic rocks which appear in conglomerates of early to middle Miocene age. As a consequence of the general rarity of unmetamorphosed dyke and volcanic rocks in the Eastern Alps, they have a high significance as provenance indicators, but thus far they have not been investigated in detail. According to texture, chemical composition and age of formation two major groups of intermediate volcanic rocks (and dyke rocks displaying porphyritic texture) can be distinguished in the Eastern Alps. The first one is represented by metamorphosed Permomesozoic, mainly tholeiitic dyke rocks, which occur in the Austroalpine crystalline basement west and south of the Tauern window (e.g. Purtscheller and Rammlmair, 1982). The second major group belongs to the prominent calc-alkaline Periadriatic magmatism which was generated between *c*. 40 and 25 Ma along the Periadriatic lineament, with a pronounced peak around 30 Ma (e.g. Dal Piaz *et al*., 1988; von Blanckenburg and Davies, 1995). Their erosional products, which were deposited as alluvial sediments (conglomerates and sandstones) in the Eastern Alpine Molasse basin, allow a well-constrained reconstruction of source terrains and palaeodrainage patterns. The major aim of this study is to describe the correlation between the dyke occurrences in the Alps and the volcanogenic pebbles in the foreland molasse, and to reveal their palaeogeographic meaning. Similar provenance studies have been carried out by Mair *et al*. (1996) on andesite and dacite pebbles of the Lower Inntal Tertiary, an Oligocene intramontane basin (Fig. 1). Mair *et al*. (1996) reconstructed source areas for the volcanic pebble assemblage based on petrographic features, concluding that there was a precursive Palaeo-Inn drainage system in Oligocene times. Therefore, a second objective of this paper is to check whether the volcanic pebbles in the foreland can be correlated with the occurrences in the Lower Inntal Tertiary, and whether they provide similar provenance indications.

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Methods and results

Samples were collected in alluvial conglomerates of late Oligocene to middle Miocene age within the Eastern Alpine Molasse zone (Wachtberg-, Kobernausser-conglomerates, Fig. 1) and the Lower Inntal Tertiary. We characterized the different types of volcanic pebbles according to their petrography and geochemical composition (X-ray fluorescence and ICP-MS analysis; see details in Brügel, 1998). Geochronological data obtained by K/Ar, Ar/Ar and fission track methods yielded further essential information on formation ages and postmagmatic thermal evolution.

Phenotypes, petrography and geochemistry

In the Eastern Alpine Molasse two general phenotypes of volcanic to subvolcanic rocks occur as pebbles in alluvial conglomerates. Texture, mineral association and postextrusive history allow a classification into two groups. Group A is a nonmetamorphosed suite of porphyritic andesites and dacites with a mineral composition of plagioclase, amphibole, biotite, quartz, opaques and accessory minerals. Minor amounts of potassic feldspar and chlorite (replacing biotite) occur. Some examples display a subvolcanic texture with lath-shaped plagioclase and can be classified as latites/trachy-andesites or hypabyssal monzonites. Hydrothermal overprint and weathering are weak and most pebbles are rather fresh. Group B is represented by fine-to medium-grained varieties of amphibole–andesitic composition. They are characterized by a metamorphic and hydrothermal overprint. Amphibole, plagioclase and biotite are altered strongly; chlorite is frequent as an alteration

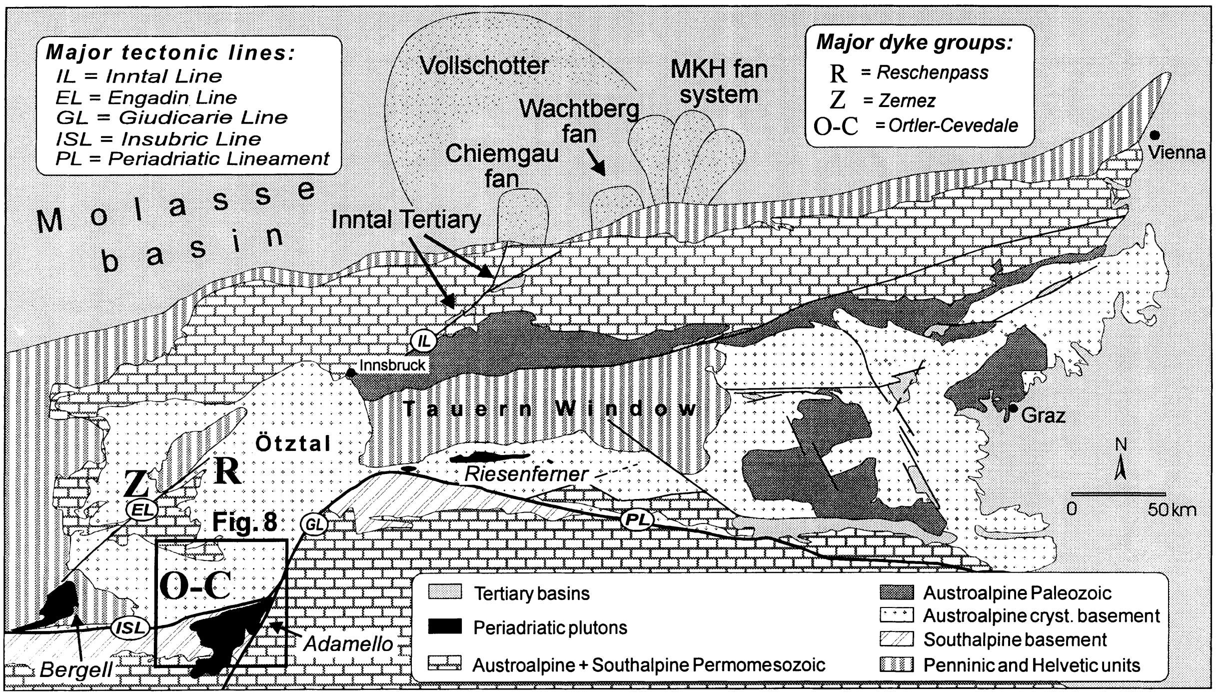

Fig. 1 Simplified geological map of the Eastern Alps. MKH, Munderfinger, Kobenausser, Hausruck fan system.

product. Magmatic pyroxene was observed as a relic in just one pebble.

The petrographic differences between group A and B are emphasized by their different geochemical characteristics. Group A shows the characteristics of high-K/shoshonitic calc-alkaline magmatism, characterized by Zr contents < 200 ppm and TiO_2 contents < 1% (Figs 2 and 3). The geochemical features concur with those of the Tertiary Periadriatic volcanic series (Beccaluva *et al.*, 1983). In contrast, group B has Zr contents > 200 ppm, TiO_2 contents > 1% for samples < 65% SiO_2, and low-to medium-K affinity.

The rare earth element distribution of group A pebbles shows uniform chondrite-normalized fractionation patterns (Fig. 4). The comparatively high ΣREE contents and the moderate fractionation

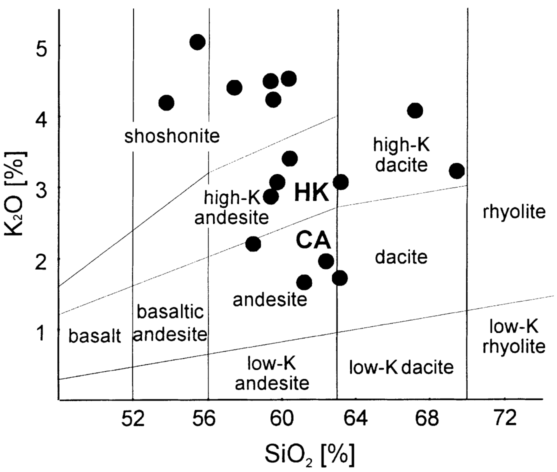

Fig. 2 Classification of nonmetamorphosed volcanic pebbles according to Peccerillo and Taylor (1976). HK, high-K; CA, calc-alkaline.

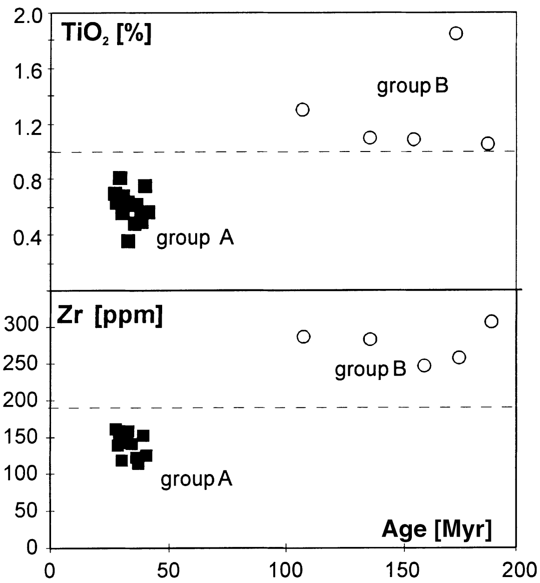

Fig. 3 Andesite and dacite pebbles of both groups discriminated by their age and Ti or Zr content, respectively.

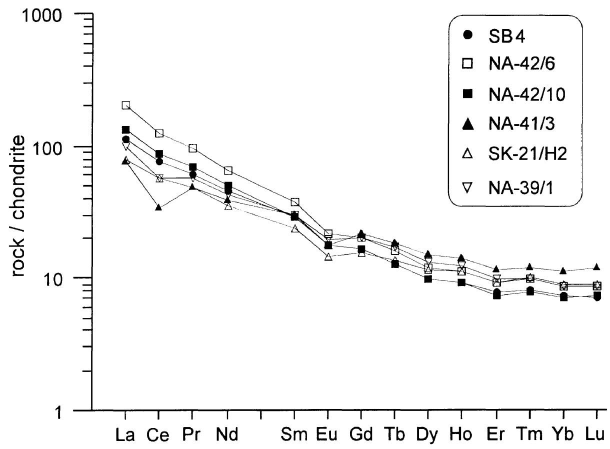

Fig. 4 Chondrite normalized REE plot of volcanic pebbles of Group A. Normalizing values after Nakamura (1974). Based on data table in Brügel (1998).

ratios ($[La/Lu]_{cn}$ between 6.25 and 22.2) suggest a continental or continental margin setting in their formation (Henderson, 1984). In order to further characterize group A, microprobe analysis was carried out on unaltered amphiboles (sample SB 4). The amphiboles show a distinct zonation, dominated by substitution of Fe and Mg. They are classified, according to the IMA nomenclature of Leake (1978), as ferroan pargasites in the outer rims and magnesian hastingsitic hornblende in the inner rims (Fig. 5). The cores are magnesian hastingsitic hornblende, on one side, and magnesian hastingsite, on the other. A similar zonation pattern was described by Mair (1991) from amphiboles of Periadriatic andesites in the Ortler region (southwestern Austroalpine basement; see Fig. 1 and discussion).

Geochronology

Age determinations were carried out on 14 pebbles of group A and on 6 pebbles of group B applying several geochronological methods (Table 1). Distinct age clusters characterize both groups. Group A yielded K/Ar whole rock ages of 24–40 Myr. As a consequence of possibile Ar loss or excess Ar, these ages are considered to be an approximation. A more precise age of 32.3 ± 0.3 Myr was revealed by Ar/Ar amphibole analysis on the sample SB 4. Apatite fission track age for this sample is 32 ± 2 Myr. The unshortened fission track lengths (Fig. 6) indicate that no thermal overprint occurred and that the obtained age is, in fact, the age of formation. One of the apparently oldest samples with a K/Ar whole rock age of 40 Myr (NA-28/G2) derives from the Lower Inntal Tertiary and corresponds with the abovementioned andesite pebbles, which were studied by Mair *et al.* (1996). This age may reflect the comparatively strong alteration of the rock or indicates derivation from a source related to the Adamello intrusive body (Fig. 1), from which formation between 43 and 32 Ma have been reported (Dal Piaz *et al.*, 1988). However, the ages of the pebbles concur with the known range for the Periadriatic magmatic activity with its pronounced peak at around 30 Ma (e.g. von Blanckenburg and Davies, 1995) (see below).

Group B yielded K/Ar whole rock ages between 187 and 121 Myr. These ages are regarded either to reflect formation of dykes during the Penninic rifting phase (mainly Jurassic) or thermal overprint during Eoalpine metamorphism (Cretaceous), which is widespread in the Austroalpine realm. They may also be interpreted as mixed ages. No apatite fission track ages are available for these samples. Large amounts of colourless, euhedral, volcanogenic zircon crystals in Lower Egerian to Eggenburgian sandstones of the Lower Inntal Tertiary (sedimentation at approximately 28–18 Ma) yield fission track cooling ages around 30 Myr (Frisch *et al.*, 1999). These zircon crys-

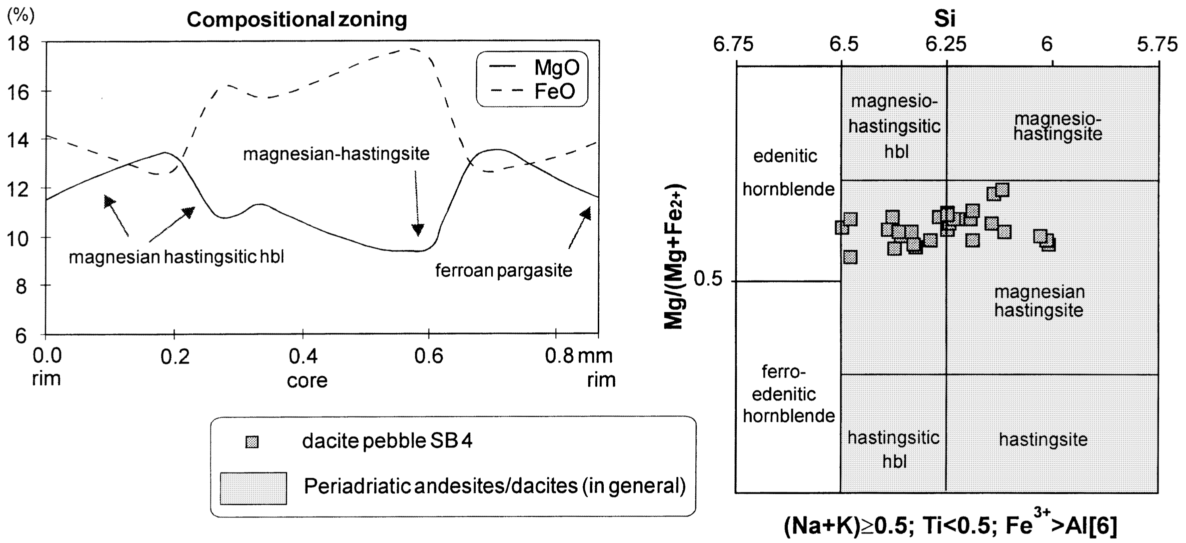

Fig. 5 Amphibole composition of andesite pebble SB4 and comparison with data of amphiboles of Periadriatic dyke rocks (Mair, 1991).

Table 1 Geochronological results of volcanic pebbles. Detailed data tables can be found in Brügel (1998)

Code	Conglomerate	Rock type	Method	Age (Myr)
Group A: nonmetamorphosed volcanic pebbles				
NA-28/G2	Lower Inntal Tertiary	Andesite	K/Ar (w.r.)	40.0 ± 1.9
NA-34/3	Munderfinger	Andesite	K/Ar (w.r.)	37.2 ± 1.5
HL 23	Munderfinger	Basalt. trachy-andesite	K/Ar (w.r.)	31.8 ± 1.5
NA-38/5	Kobernausser	Andesite	K/Ar (w.r.)	24.8 ± 1.3
NA-39/1	Kobernausser	Andesite	K/Ar (hbl)	37.7 ± 1.5
NA-41/3	Hausruck	Andesite	FT (zircon)	37.8 ± 2.3
NA-42/6	Wachtberg	Trachy-andesite	K/Ar (w.r.)	33.0 ± 1.3
NA-42/10	Wachtberg	Andesite	FT (apatite)	29.1 ± 2.1
SB 4	Wachtberg	Trachy-andesite	Ar/Ar (hbl)	32.3 ± 0.3
SK21H2	Chiemgau	Andesite (hypabyssal diorite)	K/Ar (w.r.)	35.8 ± 1.5
SK21H11	Chiemgau	Dacite (hypabyssal grano-diorite)	K/Ar (w.r.)	30.8 ± 1.2
TB 1	'Südl. Vollschotter'	Basalt. trachy-andesite	K/Ar (w.r.)	29.5 ± 1.1
TB 2	'Südl. Vollschotter'	Andesite	K/Ar (w.r.)	29.5 ± 1.2
TB 3	'Südl. Vollschotter'	Dacite	K/Ar (w.r)	40.5 ± 4.0
Group B: Metamorphosed volcanic pebbles				
NA-34/2	Munderfinger	Andesite	K/Ar (w.r.)	121 ± 4.6
NA-41/7	Hausruck	Basaltic andesite	K/Ar (w.r.)	174 ± 6.6
NA-42/4	Wachtberg	Subvolcanic trachy-andesite (hypabyssal monzonite)	K/Ar (w.r.)	136 ± 5
NA-42/8	Wachtberg	Subvolcanic andesite	K/Ar (w.r.)	159 ± 6
TB 4	'Südl. Vollschotter'	Andesite	K/Ar (w.r.)	108 ± 4.3
TB 5	'Südl. Vollschotter'	Dacite	K/Ar (w.r.)	187 ± 13

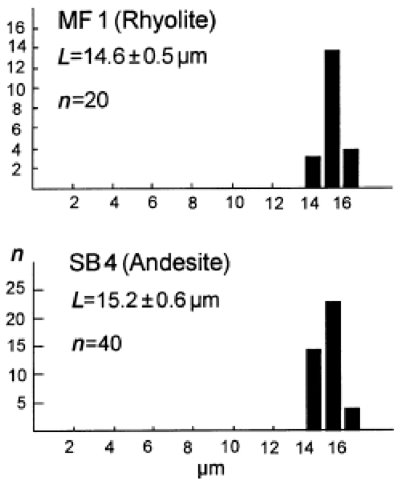

Fig. 6 Confined fission track length in apatites of rhyolite pebble MF 1 and andesite pebble SB 4. Both distributions are composed of unshortened tracks and indicate fast cooling and lack of any postsedimentary thermal overprint of the Munderfing and Wachtberg conglomerates.

tals are typical of Periadriatic igneous rocks and indicate substantial erosion of Periadriatic volcanic lithologies in late Oligocene and early Miocene times.

Discussion of provenance and reconstruction of a volcanic chain

Permomesozoic and Palaeogene volcanic suites are represented by the alluvial pebbles. The discrimination between both groups becomes evident by their distinct geochemical characteristics and ages (Fig. 3). All andesite/dacite pebbles with TiO_2 contents < 1% and Zr contents < 200 ppm yield K/Ar, Ar/Ar and FT ages between 24 and 40 Myr. In contrast, those with > 1% TiO_2 and Zr contents > 200 ppm have K/Ar ages > 100 Myr. The outlined congruence between intermediate calc-alkaline/high-K volcanic pebbles of the foreland molasse (group A) and dyke rocks from the Periadriatic belt, corroborate their clear relationship. Today, widespread Periadriatic nonmetamorphosed porphyritic andesites and dacites are exposed in the Ortler-Cevedale basement west of the Giudicarie lineament (Fig. 1). In addition to their similar ages, these rocks show also similar phenocryst habits. The dykes of the Ortler region contain magnesio hastingsites or magnesio hastingsitic hornblendes (Purtscheller and Mogessie, 1988; Mair, 1991), or pargasitic to hastingsitic varieties (Dal Piaz *et al.*, 1988). Moreover, the characteristic zonations of amphiboles in the andesite pebbles (see Fig. 5) and the dykes of the Ortler region (Mair, 1991) are nearly identical. The pebbles with bulk K_2O contents of over 3% are assumed to derive from dykes in the immediate vicinity to the Periadriatic line, because those dykes further away from the lineament obviously show lower K-values (< 2.5% K_2O; Dal Piaz *et al.*, 1988; Mair and Purtscheller, 1995) (see Fig. 8). The occurrence of Late Alpine (Periadriatic) coarse-grained porphyritic volcanic rocks in Molasse conglomerates has an important impact on the reconstruction of the uplift history and geomorphological evolution of the Eastern Alps, because these rocks are not exposed in the present catchment area of the Eastern Alpine north-bound drainage system (Inn-Salzach-Enns system, Fig. 7a). The dykes exposed in the catchment area of the present-day Inn river (Zernez and Reschenpass regions, see Fig. 1) display metamorphic overprints and contain relictic pyroxene rather than amphibole as a primary magmatic phase in the intermediate types. K/Ar whole rock analysis has revealed Mesozoic ages (Zöldföldi, 1998). Today, the basement units comprising the Periadriatic magmatic belt are drained to the south by the Etsch-Adda system and to the east by the Drau system (Fig. 7a). From the occurrences in the Molasse zone we conclude that the central section of the Periadriatic magmatic belt (between Bergell and Rieserferner intrusions, Fig. 1) were drained to the north in early to late Miocene times (Fig. 7b). Textures, FT and K/Ar ages of subvolcanic Bergell rocks (and corresponding pebbles) which were deposited south of the Alps

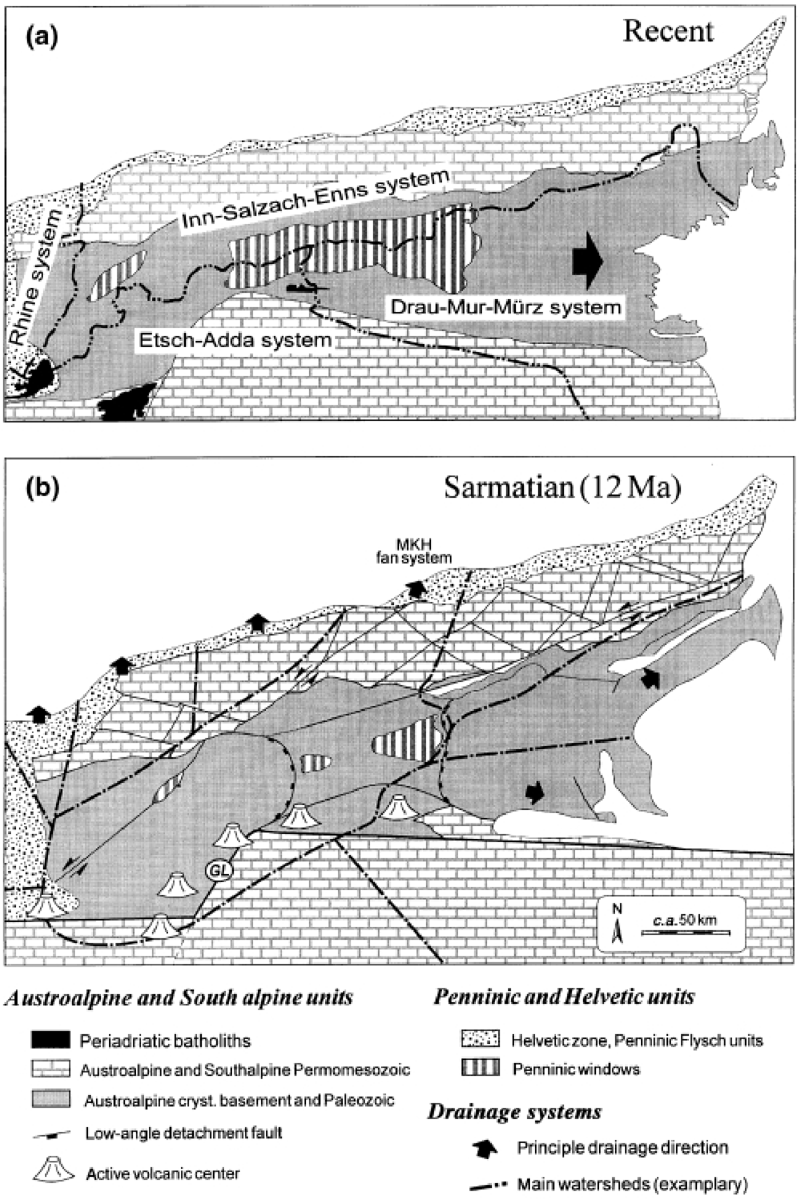

Fig. 7 The main watersheds and drainage systems of the Eastern Alps. (a) Present-day situation; (b) drainage pattern of the Eastern Alps in Miocene times ($\sim$12 Ma). Noticeably, only a part of the recent Tauern Window exhumed to the surface (mainly metasedimentary rocks) and the main watershed is situated south of its recent position (cf. Fig. 7a). The Palaeo-Inn transported a part of the Periadriatic intrusives to the northern Molasse basin, mainly into the MKH fan system. GL = Giudicarie Line; palinspastic reconstruction after Frisch *et al.* (1998).

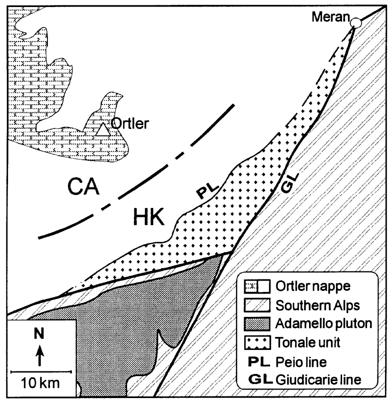

Fig. 8 Simplified geological map of the Ortler region showing the calc-alkaline (CA) and high-K (HK) zonation of Periadriatic dykes (after Dal Piaz *et al.*, 1988).

(Giger and Hurford, 1989), are remarkably similar to the subvolcanic pebbles from the Chiemgau conglomerate in the Molasse zone north of the Alps. For early Miocene times this implies that eroded material from the Periadriatic magmatic belt was transported into the northern as well as the southern foreland basins. Consequently, the main watershed at that time must have been situated along the Periadriatic belt in the Bergell region. This implies that it took its course much further south than today. Considering the pebbles from the intramontane Lower Inntal Tertiary (Mair *et al.*, 1996) and those from the Molasse belonging to group A a relationship between both is obvious. Although the former are strongly altered, they display rather identical chemical signatures (Mair *et al.*, 1996; sample NA-28/G2) and Periadriatic formation ages (Table 1). Mair *et al.* (1996) suggested the Reschenpass and/or Ortler region as source areas, but, as outlined above, the Reschenpass area can be excluded because of the Mesozoic age of these dykes. The Ortler region is a feasible source area but other areas, in particular the eroded parts above the Bergell, Adamello, Rensen and Riesenferner plutons, are good source candidates as well.

We believe that the high amount of euhedral zircon crystals with FT ages around 30 Myr, from sandstones of the Lower Inntal Tertiary, derive from a volcanic chain which traced the Periadriatic lineament nearly along its entire length (Dunkl *et al.* submitted). The volcanogenic crystals provide evidence for syn-to postcollisional calc-alkaline volcanism in the Eastern Alps and, in contrast to the present situation, widespread distribution of volcanic lithologies. In this context we argue that the andesite and dacite pebbles in the Inntal Tertiary and the Eastern Alpine Molasse zone derive from volcanic edifices and subvolcanic dyke swarms that probably topped the Periadriatic intrusive bodies. This leads to the idea of an important volcanic chain along the lineament that was completely destructed during late Oligocene and early Miocene erosion. The presently exhumed plutonic level was buried beneath several kilometres of rock at the time of emplacement and volcanism (Elias, 1998).

Conclusion

The andesite and dacite pebbles in Eastern Alpine Molasse conglomerates suggest a palaeodrainage system in early to late Miocene times which drained the present southwestern Austroalpine realm in a northerly to north-easterly direction. Today, this area is drained to the south into the Adriatic Sea. The main E–W running watershed of the Eastern Alps was situated considerably farther south than today. The northward shift of the watershed did not occur before late Miocene times, because the Sarmatian/Pannonian conglomerates in the northern Molasse zone (MKH fan system) still contains volcanic pebbles of Periadriatic derivation.

The volcanic record in Miocene foreland deposits testifies to intense volcanic activity along the Periadriatic lineament and suggests a chain of volcanoes. Exhumation in the order of several kilometres along the middle section of the lineament in the last 20 Myr suggests that these volcanoes are now eroded completely.

Acknowledgements

The German Science Foundation supported this study in the frame of the Collaborative Research Centre 275. Thanks to L. Ratschbacher (Freiberg) for the Ar/Ar measurement performed on a horblende sample. Constructive reviews by F. Schlunegger (Jena) and an unknown reviewer were much appreciated and improved both content and style.

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Received 19 November 1999; revised version accepted 31 May 2000

